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PROGRESS REPORT n° 3

INSTRUMENTS S.A

DIVISION

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o/ref. JF/AB

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CONTINUATION OF THE STUDY OF REFLECTING DIFFRACTION GRATINGS BY THE APPLICATION OF HOLOGRAPHIC TECHNIQUES.

PROGRESS REPORT n° 3

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STUDY OF THE EFFICIENCY FOR TRIANGULAR PROFILE GRATING

1 - Study of the relative efficiency : D function

a) Conventions used

It is first necessary to precise the convention used for the grating law. Effectively the authors who have worked on the problem of grating efficiency generally use a convention which is different from the one we have used up to now.
See Fig. 1

α is the incidence angle
β_N is the diffracted angle by reflexion in order N
θ_N is the diffracted angle by transmission in order N

α is counted positively with respect to the normal in the first quadrant and negative in the second quadrant.
β_N is positive in the second quadrant and negative in the first
θ_N is positive in the third quadrant and negative in the fourth .

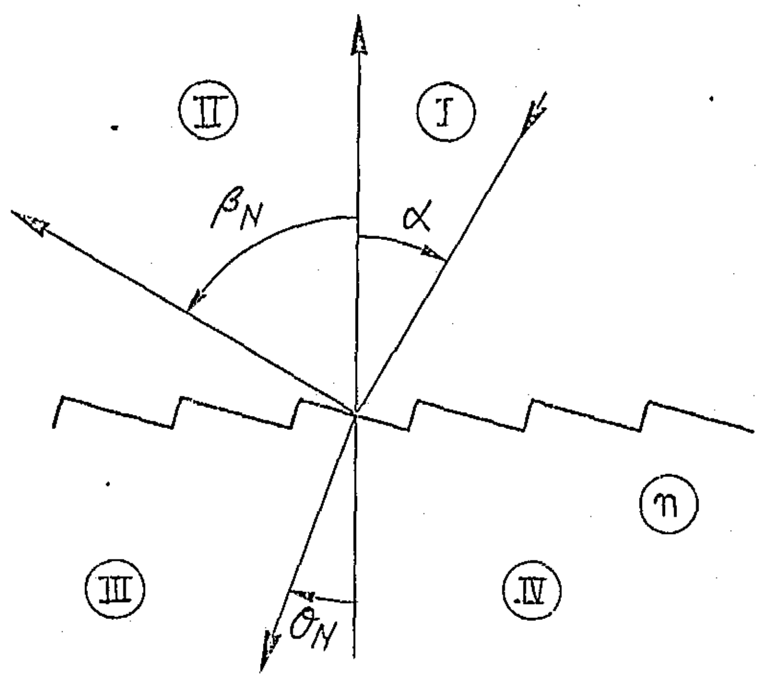


Fig. 1

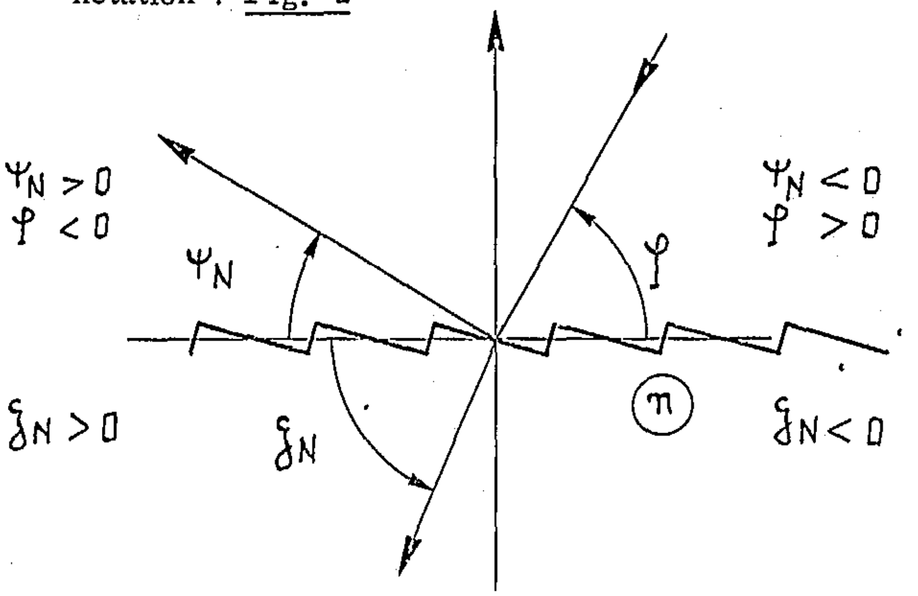
We have, if " a " is the groove spacing and n the refraction indice of the grating :

(1) $$a\ (\sin \beta_N - \sin \alpha) = N \lambda$$

(2) $$a\ (n \sin \theta_N - \sin \alpha) = N \lambda$$

- with this type of convention the blazed orders are negative for a "direct" mounting (Fig. 1) .

The same type of convention can be used with the complementary notation : Fig. 2



(3) $$\begin{cases} a\ (\cos \Psi_N - \cos \varphi) = N \lambda \\ a\ (n \cos \delta_N - \cos \varphi) = N \lambda \end{cases}$$
(4)

.../..

b) Calculation of the relative efficiency

We suppose a plane wave falling on an echelette grating. The nagle of incidence is α and we want to calculate the energy diffracted in the direction β_N of a given order supposing that the reflectivity of the coating is 100%.

Supposing that the ratio $\frac{\lambda}{a}$ is smaller than 0, 1 at least, we consider that the amplitude diffracted can be calculated through Huygens-Fresnel principle : the amplitude in the β_N direction is the sum of the amplitude diffracted by each element of the facet (Fig. 3) :

$$dA = k \times A_0 \times e^{2\pi j \cdot \frac{\delta(x)}{\lambda}} \times dx$$

$$\delta_{(x)} = MH - MH' =$$

$$= x \sin(\alpha - \gamma) - x \sin(\beta_N + \gamma)$$

The origin of phase being in 0.

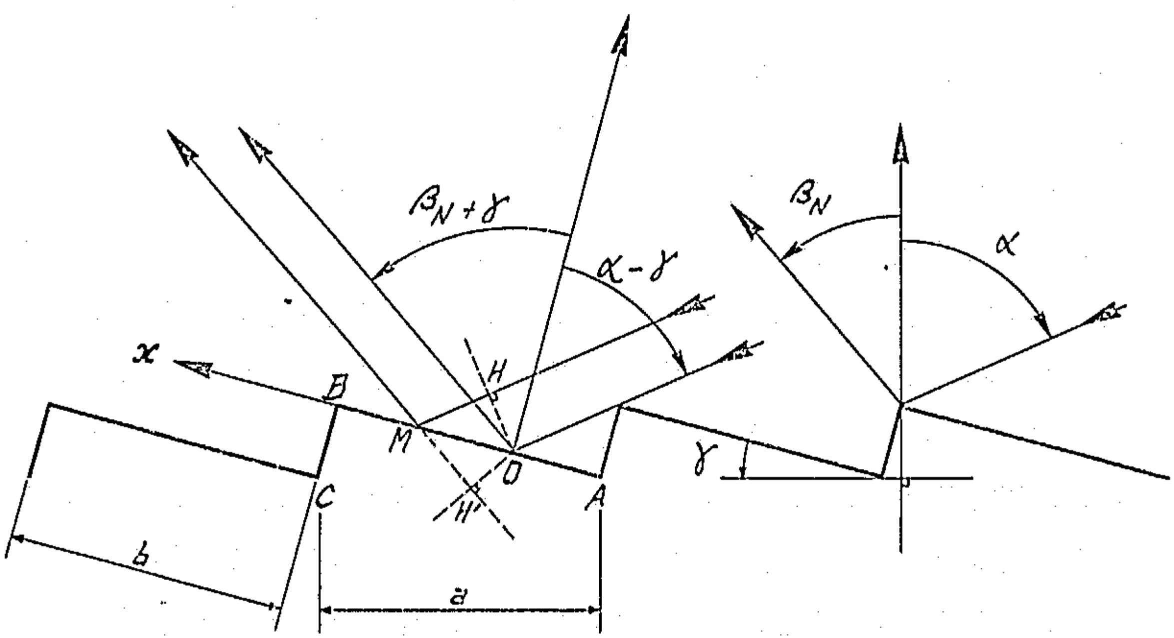


Fig. 3

Only the part $b^* = OB$ of the facet b contributes to the diffraction in the direction β_N..

We have $OB = AB - AO$

$AB = a \cos\gamma$

$AO = BC \, tg(\alpha - \gamma) = a \sin\gamma \, . \, tg(\alpha - \gamma)$

$\rightarrow OB = b^* = a\left(\cos\gamma - \sin\gamma \, tg(\alpha - \gamma)\right)$

(5) $$\rightarrow \delta = \frac{b^*}{a} = \cos\gamma - \sin\gamma \, tg(\alpha - \gamma)$$

Then we can write the expression of the amplitude diffracted :

$$A = k A_o \int_0^{b^*} e^{\frac{2\pi j}{\lambda}\left[\sin(\alpha - \gamma) - \sin(\beta_N + \gamma)\right]x} \, . \, dx$$

$$A = k A_o \left[\frac{e^{\frac{2\pi j}{\lambda}\left[\sin(\alpha - \gamma) - \sin(\beta_N + \gamma)\right]x}}{\frac{2\pi j}{\lambda}\left[\sin(\alpha - \gamma) - \sin(\beta_N + \gamma)\right]}\right]_0^{b^*}$$

$$A = k A_o \frac{e^{\frac{2\pi j}{\lambda}\left[\sin(\alpha - \gamma) - \sin(\beta_N + \gamma)\right]b^*} - 1}{\frac{2\pi j}{\lambda}\left[\sin(\alpha - \gamma) - \sin(\beta_N + \gamma)\right]}$$

.../..

$$A = kA_0 \frac{e^{\frac{\pi j}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]b^*} - e^{-\frac{\pi j}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]b^*}}{\frac{2\pi j}{\lambda}\sin(\alpha-\gamma)-\sin(\beta_N+\gamma) \times e^{-\frac{\pi j}{\lambda}\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)}}$$

$$A = kA_0 \frac{\sin\frac{\pi}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]b^*}{\frac{\pi}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]} \times e^{\frac{\pi j}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]b^*}$$

The energy diffracted in the order N is then proportional to the quantity:

$$D_N \simeq \frac{A\ A^*}{A_0^2} = k^2 \times \left[\frac{\sin \pi\frac{b^*}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]}{\frac{\pi}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]}\right]^2$$

(6) $$D_N = k^2 \times \left(\frac{\sin\frac{\pi\ b^*}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]}{\frac{\pi}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]}\right)^2$$

k^2 is then determined by the relation :

(7) $$\sum_{-N_1}^{+N_2} D_N = 1$$

- In practice we have found empirically that D_N can be approximated in a rather satisfactory manner by the expression :

(8) $$D_N = f^2 \times \left(\frac{\sin\frac{\pi\ b^*}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]}{\frac{\pi\ b^*}{\lambda}\left[\sin(\alpha-\gamma)-\sin(\beta_N+\gamma)\right]}\right)^2$$

up to angle of incidence reaching 80°.

To obtain the expression, it is only necessary to replace k by $\frac{1}{a}$ in the preceding calculation.

.../..

To test the validity of expression (8) we have calculated ΣD_N for several values of α for a 1200 gr/mm grating blazed at 1000 A°, $\gamma = 3.44°$ and for the wavelength 500 A°.

We have found :

$\alpha = 20°$	ΣD_N	$\simeq$	0.97
$\alpha = 60°$	ΣD_N	$\simeq$	0.96
$\alpha = 80°$	ΣD_N	$\simeq$	0.85
$\alpha = 88°$	ΣD_N	$\simeq$	0.30

The expression (8) remains valid up to 80° incidence with an error lower than 20%.

The same calculation done for a 5000 gr/mm, blazed at 1000 A° $\gamma = 14.48°$ and for wavelength 500 A° has given :

$\alpha = 20°$	ΣD_N	$\simeq$	0.94
$\alpha = 60°$	ΣD_N	$\simeq$	0.84
$\alpha = 80°$	ΣD_N	$\simeq$	0.47
$\alpha = 88°$	ΣD_N	$\simeq$	0.08

The expression (8) is normalized in this case for lower incidence angles : 60°. For higher angles it would be better to use expression :

$$D_N = \rho^2 \cdot \left(\frac{\sin \frac{\pi f^*}{\lambda} \left[\sin(\alpha-\gamma) - \sin(\beta_N+\gamma) \right]}{\frac{\pi f^*}{\lambda} \left[\sin(\alpha-\gamma) - \sin(\beta_N+\gamma) \right]} \right)^2 \times \frac{1}{\Sigma D_N}$$

.../..

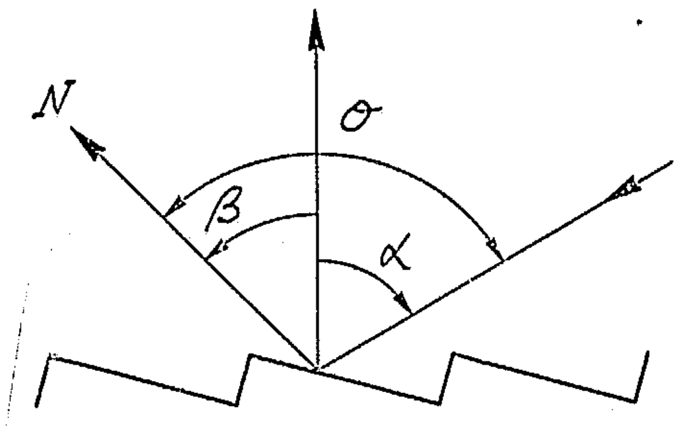
In practice we shall see from some few examples that the expression (8) leads to results generally more realistic.

Numerical applications

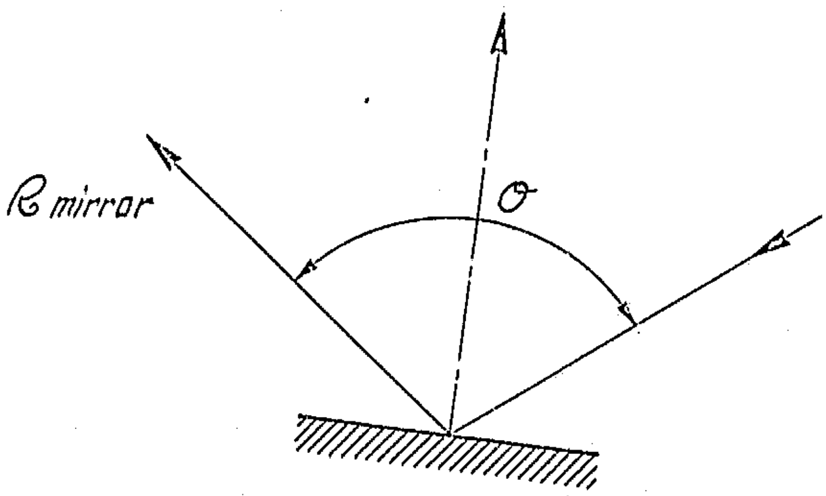
On graphs p. 18 to25, we have drawn (1) $D_N = f(\alpha)$ for λ = 500 A° and λ = 250 A° for 600 gr/mm, 1200 gr/mm, 2400 gr/mm, 5000 gr/mm gratings, blazed at 1000 A° and α varying between O and 88°. The blaze angles corresponding to each grating are respectively : 1.71° - 3.44° - 6.89° and 14.48°.

We can see from these curves that, for a given wavelength, the angle of incidence for the optimum relative efficiency is sensibly the same for the various gratings independently of the Nb grooves/mm. In spite of the fact that all these gratings are blazed at the same wavelength this was absolutely not obvious "a priori" as the blaze angle varies from γ = 1.71° for 600 gr/mm to 14.48° for the 5000 gr/mm grating.

2 - Study of the absolute efficiency by multiplying D function by the efficiency of an "equivalent mirror"



- Fig. 4 -



- Fig. 5 -

.../..

We propose to use as expression of the absolute efficiency of the grating the quantity :

(9) $$E^{m}_{N} = D_{(N)} \times \mathcal{R}_{\text{mirror}}$$

$\mathcal{R}$ mirror being the reflectivity of a mirror which deviates the incident beam of the same angle as the grating in the given order (Fig.4.5) that is to say the reflectivity of a mirror working with an angle of incidence equal to :

$$i = \frac{\theta}{2} = \frac{\alpha + \beta}{2}$$

We recall (Second Progress Report) that in that case the expressions of $\mathcal{R}$ are the following :

For electric field parallel to grooves :

(10) $$\mathcal{R}_{//} = \frac{\cos^2\left(\frac{\alpha+\beta}{2}\right) - 2p\cos\left(\frac{\alpha+\beta}{2}\right) + p^2 + q^2}{\cos^2\left(\frac{\alpha+\beta}{2}\right) + 2p\cos\left(\frac{\alpha+\beta}{2}\right) + p^2 + q^2}$$

For electric field perpendicular to grooves :

(11) $$\mathcal{R}_{\perp} = \frac{\left[(\nu^2-\chi^2)\cos\left(\frac{\alpha+\beta}{2}\right) - p\right]^2 + \left[2\nu\chi\cos\left(\frac{\alpha+\beta}{2}\right) - \frac{\nu\chi}{p}\right]^2}{\left[(\nu^2-\chi^2)\cos\left(\frac{\alpha+\beta}{2}\right) + p\right]^2 + \left[2\nu\chi\cos\left(\frac{\alpha+\beta}{2}\right) + \frac{\nu\chi}{p}\right]^2}$$

with $n = \nu - j\chi$ index of coating

12) $$p^2 + q^2 = \sqrt{\left(\nu^2 - \chi^2 - \sin^2\left(\frac{\alpha+\beta}{2}\right)\right)^2 + 4\nu^2\chi^2}$$

.../..

(13) $$\rho^{2\prime} = \frac{\nu^2 - \chi^2 - \sin^2 \frac{(\alpha + \beta)}{2} + p^2 + q^2}{2}$$

Numerical applications

On graphs p.26 to 33, we have drawn $E^m_N = D_N \times R_{mirror}$ for λ = 500 A° and λ = 250 A° for gratings 600 gr/mm, 1200 gr/mm, 2400 gr/mm and 5000 gr/mm blazed at 1000 A° and α varying between 0 and 88°.

The calculations have been done for gold coated gratings using the following indices :

λ = 500 A° ν = 0.85 χ = 0.645

λ = 250 A° ν = 0.89 χ = 0.386

The calculation has not been done for Al coating because the indices given by Hunter (see Second Progress Report) are those of Al without $Al_{2}O_{3}$ oxyde and therefore are not of practical interest.

.../..

3 - Direct calculation of the efficiency for a grating

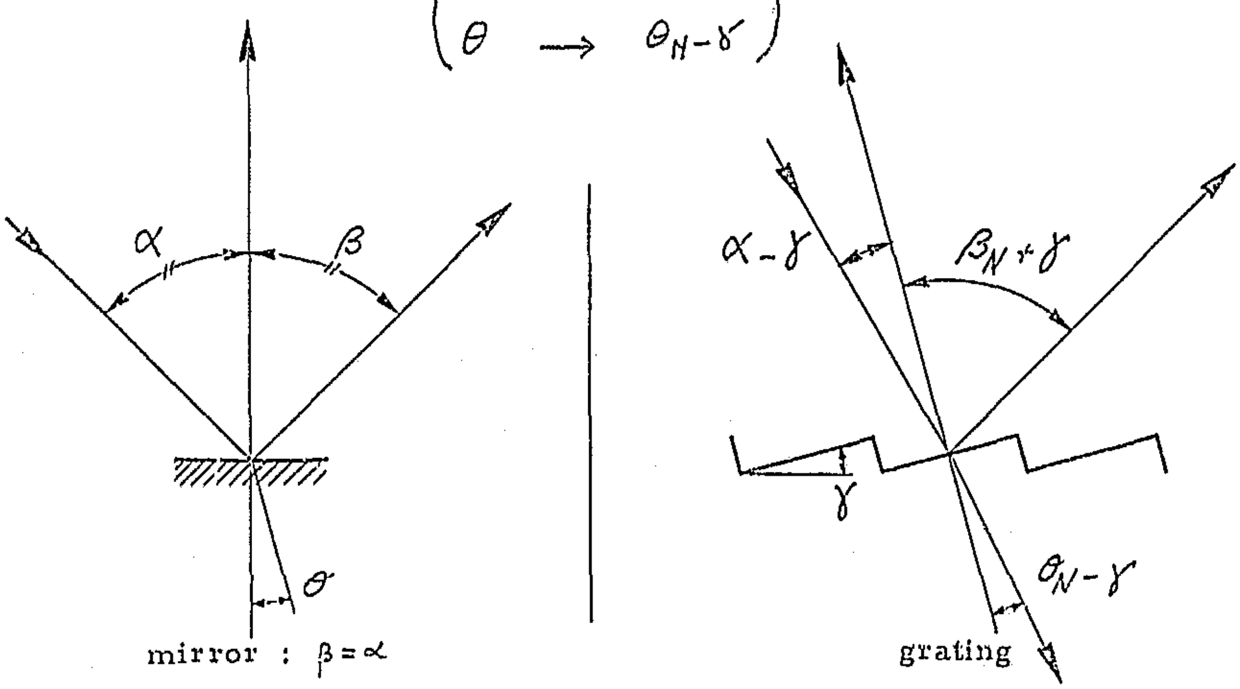
the absolute efficiency of the grating is given by the expression :

(14) $$E_N^R = D_N \times R_{(grating)}$$

The reflectivity of the facet of the grating $R_{(grating)}$ is obtained by using the Tomboulian method : this consists in calculating the reflectivity of the facet as is calculated the reflectivity of a mirror, by writing the boundary conditions of Maxwell equations for the incident field and for each pair of reflected and transmitted diffracted orders:

To go from the mirror to the grating case it is only necessary to change the various parameters in the following way :

$$\left\{ \begin{array}{lcl} \alpha & \longrightarrow & \alpha - \gamma \\ \beta & \longrightarrow & \beta_N + \gamma \\ \theta & \longrightarrow & \theta_N - \gamma \end{array} \right\}$$



So taking into account that the tangential components of electric and magnetic field are continuous at the boundary, that we have $\sqrt{\varepsilon}\ / E / = \sqrt{\mu}\ / H /$ and that E, H and the propagation vector form a right-handed orthogonal triad · we can do the same calculation as in second report Pages 7 to 10 and obtain :
see Fig. 6 :

- symbol // correpond to electric field parallel to grooves and $\perp$ to electric field perpendicular to grooves.

- index i, r and t correspond to field incident, reflected and transmitted.

- We suppose that $\mu = 1$ so $\sqrt{\varepsilon} = n$ the admittance of air is Yo = 1 and the admittance of grating $Y_1 = n$

(15) $$Ei_{//} + Er_{//} = Et_{//}$$

(16) $$Ei_{//} \cos(\alpha - \gamma) - Er_{//} \cos(\beta_N + \gamma) = n . Et_{//} . \cos(\theta_N - \gamma)$$

(17) $$Ei_{\perp} + Er_{\perp} = n \quad Et_{\perp}$$

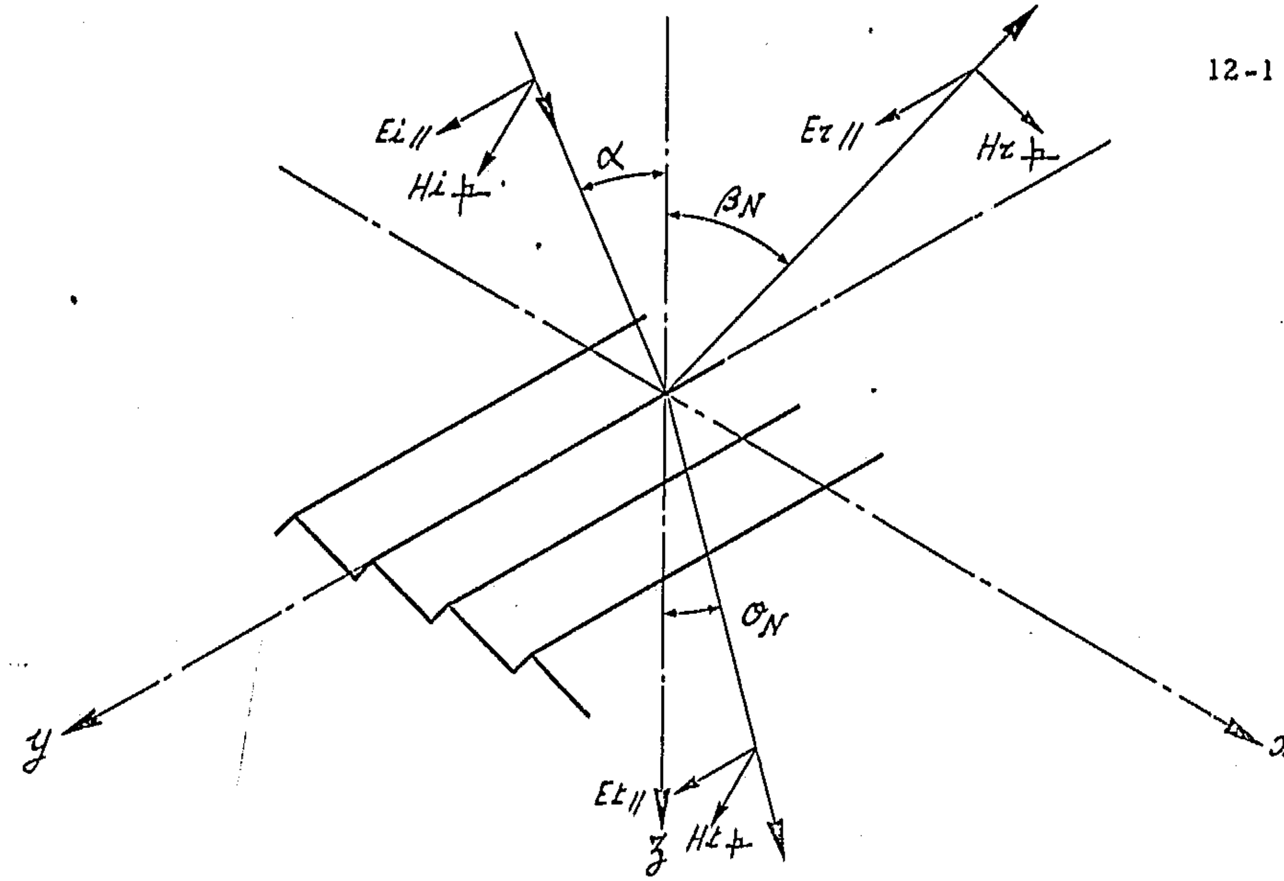
(18) $$Ei_{\perp} \cos(\alpha - \gamma) - Er_{\perp} \cos(\beta_N + \gamma) = Et_{\perp} . \cos(\theta_N - \gamma)$$

Eliminating $Et_{//}$ from (15) and (16) we obtain :

(19) $$r_{//} = \frac{Er_{//}}{Ei_{//}} = \frac{\cos(\alpha - \gamma) - n \cos(\theta_N - \gamma)}{\cos(\beta_N + \gamma) + n \cos(\theta_N - \gamma)}$$

and $R_{0 //}$ (grating) $= / r_{//} /^2$

.../..



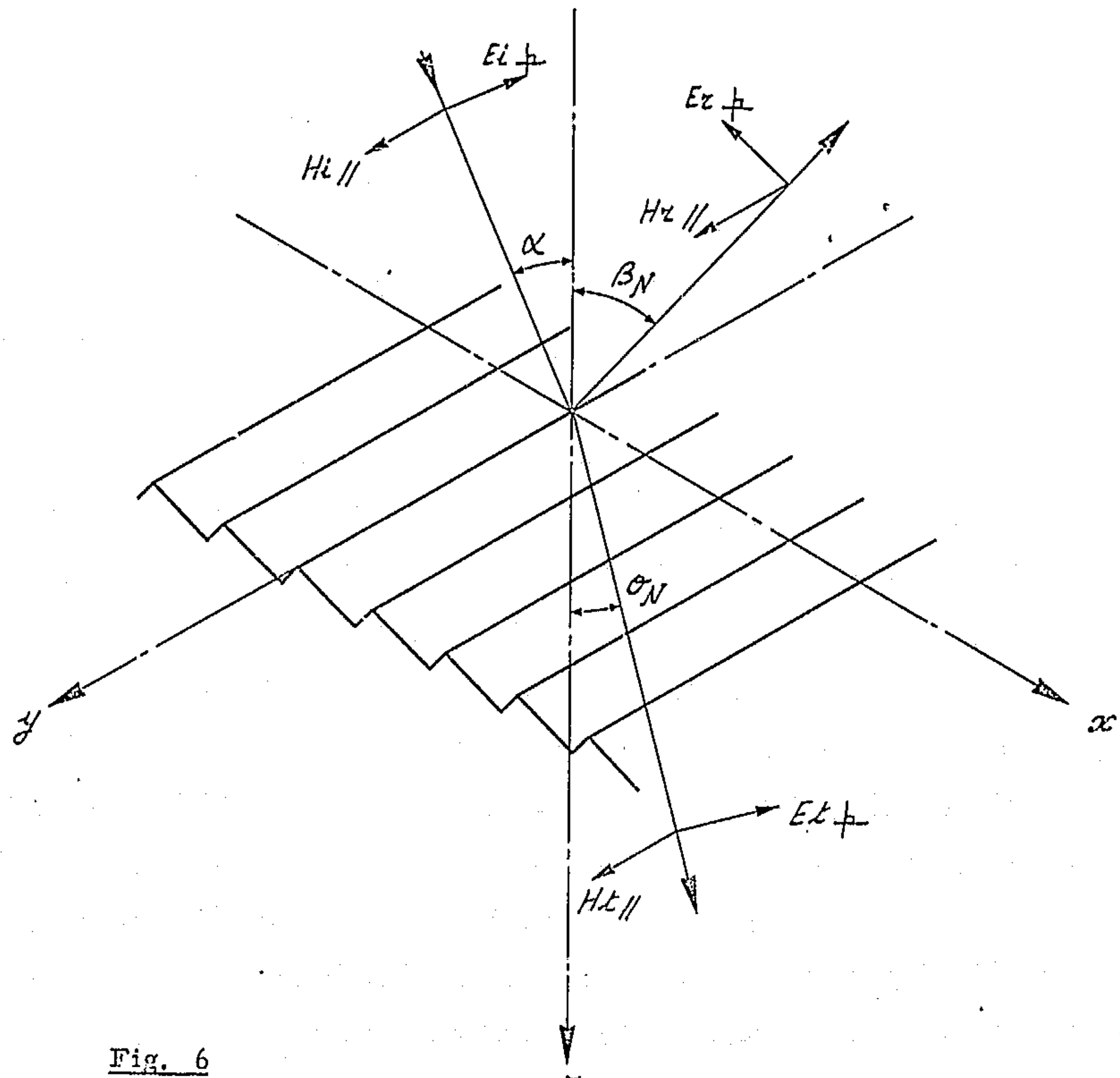


Fig. 6

Eliminating $E_t \perp$ from equations (17) and (18) we obtain :

(20) $$r_\perp = \frac{E_r \perp}{E_i \perp} = \frac{n \cos(\alpha - \gamma) - \cos(\theta_N - \gamma)}{n \cos(\beta_N + \gamma) + \cos(\theta_N - \gamma)}$$

and $$R_0 \perp_{(\text{grating})} = |r \perp|^2$$

But we have $$n = \nu - j\chi$$

(21) we call $$n \cdot \cos(\theta_N - \gamma) = p - jq$$

making the difference of equations (1) and (2) we obtain

$$n \sin \theta_N = \sin \beta_N$$

changing θ_N in $\theta_N - \gamma$ and β_N in $\beta_N + \gamma$ we obtain

(22) $$n \sin(\theta_N - \gamma) = \sin(\beta_N + \gamma)$$

This equation is only an approximation but the calculation shows that it is necessary to use it in order not to have $R_{0\,(\text{grating})}$ which becomes greater than 1 at grazing incidence when

$\delta_N = \frac{\pi}{2} - \theta_N$ is lower than γ.

.../..

In fact this is a consequence of the Tomboulian method which is an approximation and cannot be justified rigorously in electromagnetic theory.

We have :

$$(p - jq)^2 = n^2 \cos^2(\theta_N - \gamma) = n^2\left(1 - \sin^2(\theta_N - \gamma)\right)$$

using equation (22) we obtain

$$(p - jq)^2 = (\nu - j\chi)^2 - \sin^2(\beta_N + \gamma)$$

which is equivalent to the system :

$$(23) \quad \begin{cases} p^2 - q^2 = \nu^2 - \chi^2 - \sin^2(\beta_N + \gamma) \\ pq = \nu \cdot \chi \end{cases}$$

This system as yet been solved (see second report pages 11 to 13):

$$(24) \quad \begin{cases} p^2 = \dfrac{\nu^2 - \chi^2 - \sin^2(\beta_N + \gamma) + p^2 + q^2}{2} \\ q = \dfrac{\nu \cdot \chi}{p} \\ p^2 + q^2 = \sqrt{\left[\nu^2 - \chi^2 - \sin^2(\beta_N + \gamma)\right]^2 + 4\nu^2\chi^2} \end{cases}$$

It is now easy to calculate the expression of $\rho_{(grating)}$ using expressions (19) and (21) we have :

$$\rho_{//} = \left[\frac{\cos(\alpha-\gamma) - p + jq}{\cos(\beta_N+\gamma) + p - jq}\right]^2$$

(25) $$\rho_{//} = \frac{\cos^2(\alpha-\gamma) - 2p\cos(\alpha-\gamma) + p^2 + q^2}{\cos^2(\beta_N+\gamma) + 2p\cos(\beta_N+\gamma) + p^2 + q^2}$$

using expressions (20) and (21) we have

$$r_{\perp} = \frac{(\nu - j\chi)^2\cos(\alpha-\gamma) - p + jq}{(\nu - j\chi)^2\cos(\beta_N+\gamma) + p - jq}$$

$$r_{\perp} = \frac{(\nu^2-\chi^2)\cos(\alpha-\gamma) - p - j\left[2\nu\chi\cos(\alpha-\gamma) - q\right]}{(\nu^2-\chi^2)\cos(\beta_N+\gamma) + p - j\left[2\nu\chi\cos(\beta_N+\gamma) + q\right]}$$

.../..

(26) $$\mathcal{R}_{\perp} = |r_{\perp}|^2 = \frac{\left[(\nu^2-\chi^2)\cos(\alpha-\gamma) - \rho\right]^2 + \left[2\nu\chi\cos(\alpha-\gamma) - \frac{\nu\chi}{\rho}\right]^2}{\left[(\nu^2-\chi^2)\cos(\beta_N+\gamma) + \rho\right]^2 + \left[2\nu\chi\cos(\beta_N+\gamma) + \frac{\nu\chi}{\rho}\right]^2}$$

It is then possible to calculate the efficiency of the grating for the two polarisations :

(27) $$E_{N\,//} = D_{(N)} \times \mathcal{R}_{//}$$

(28) $$E_{N\perp} = D_{(N)} \times \mathcal{R}_{\perp}$$

Numerical application =

On graphs p. 34 to 41, we have drawn $E_N = D_N \times \mathcal{R}_{(\text{grating})}$ for λ = 500 A° and λ = 250 A° for 600 gr/mm, 1200, 2400 and 5000 gr/mm gratings blazed at 1000 A° and α varying from 0 to 88°.

The calculations have been done for gold coated gratings using the same indices as in the previous case :

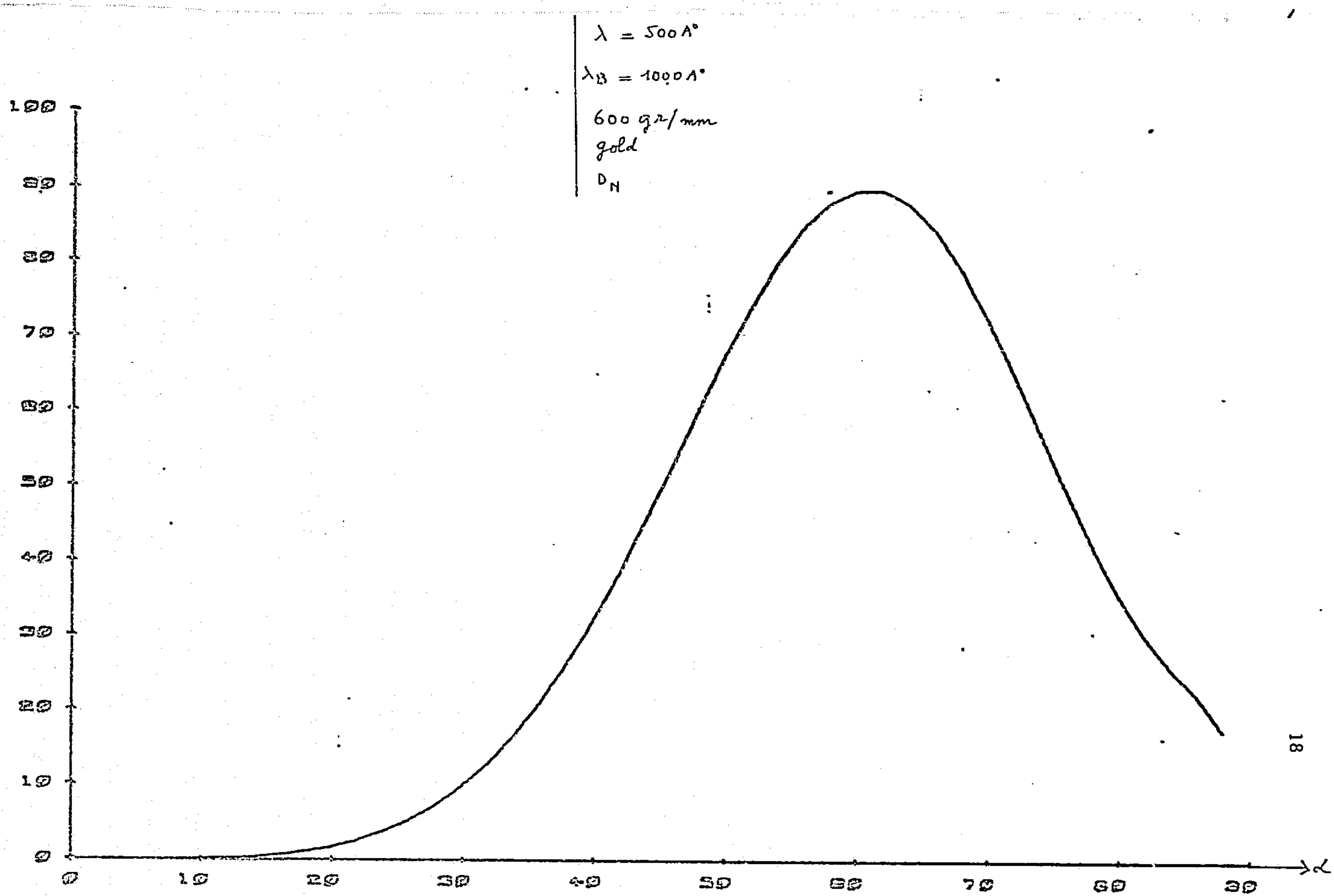
λ = 500 A°	ν = 0.85	χ = 0.645
λ = 250 A°	ν = 0.89	χ = 0.386

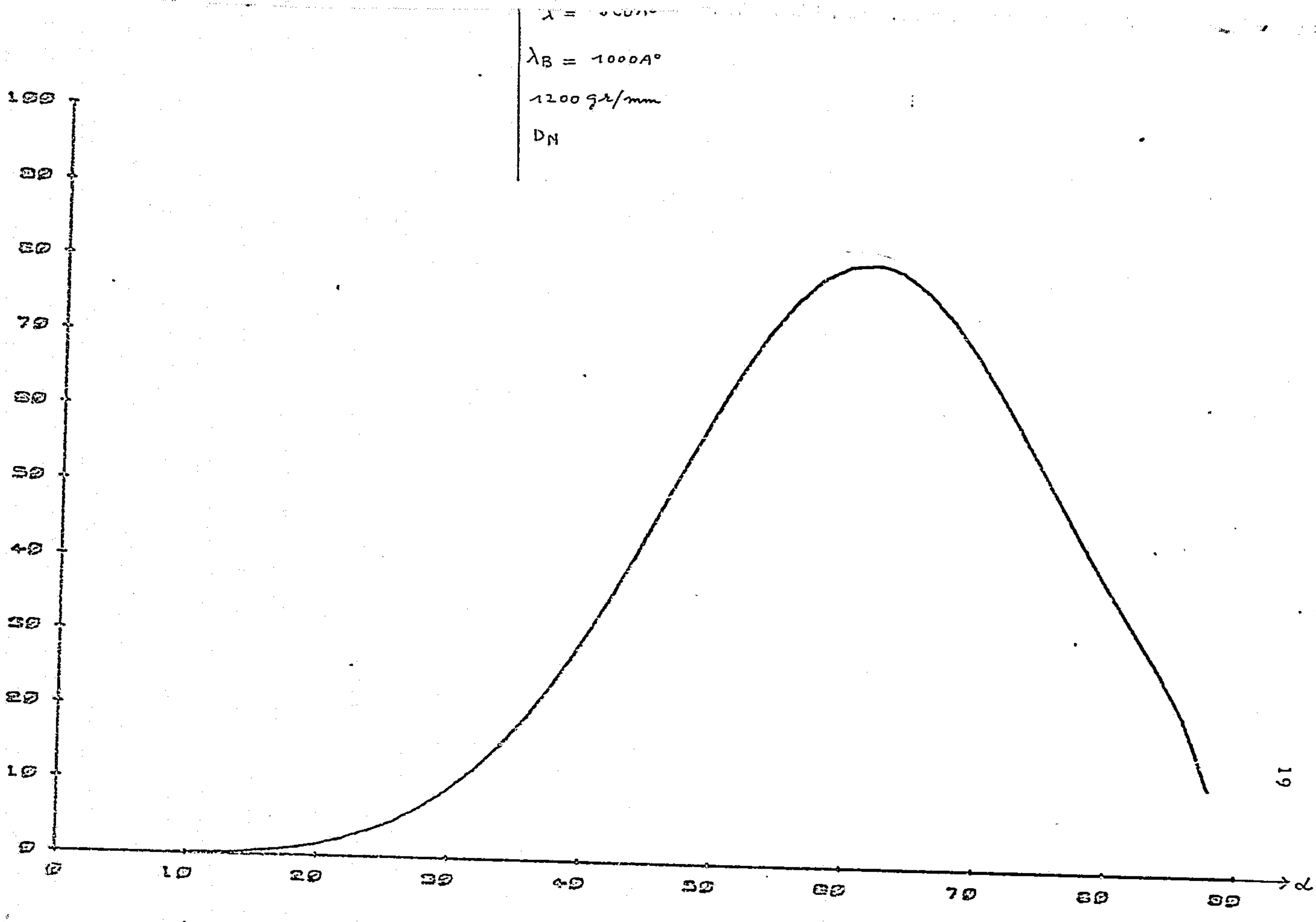
.../..

It can be seen from these curves that the efficiencies obtained by this way are very closed to those obtained in the previous paragraph with

$$E^{m}_{N} = D_{N} \times R_{o\,\text{mirror}}$$

It would be very interesting to compare the results obtained by this type of approximated theory with those obtained with rigorous electromagnetic theory as developed by Pr. Petit.


λ = 500 A°
λB = 1000 A°
600 gr/mm
gold
DN
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α


$\lambda_B = 1000A°$
1200 gr/mm
D_N
100
90
80
70
60
50
40
30
20
10
0
0
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30
40
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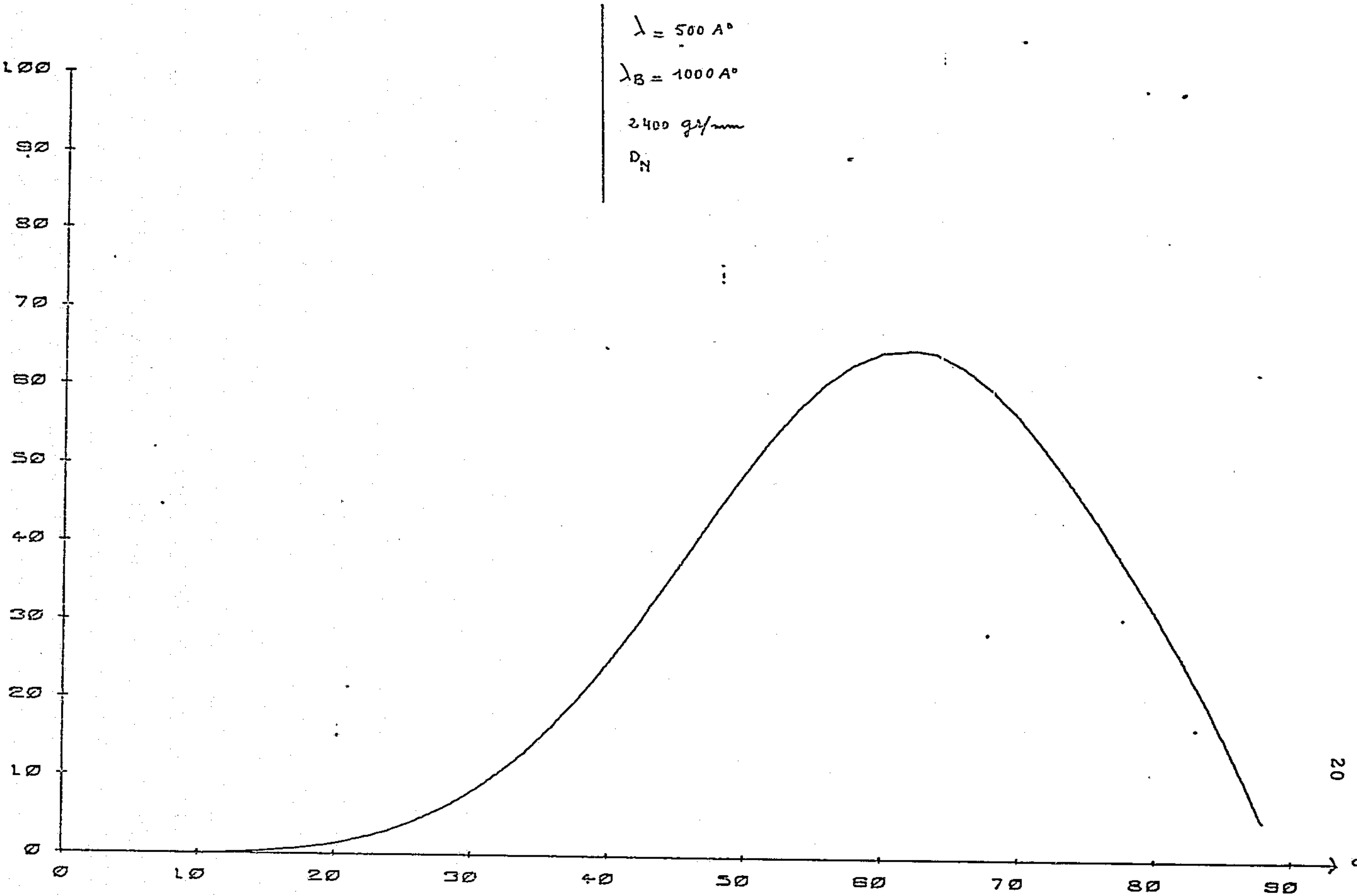
60
70
80
90
α


λ = 500 A°
λB = 1000 A°
2400 gr/mm
DN
100
90
80
70
60
50
40
30
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10
0
0
10
20
30
40
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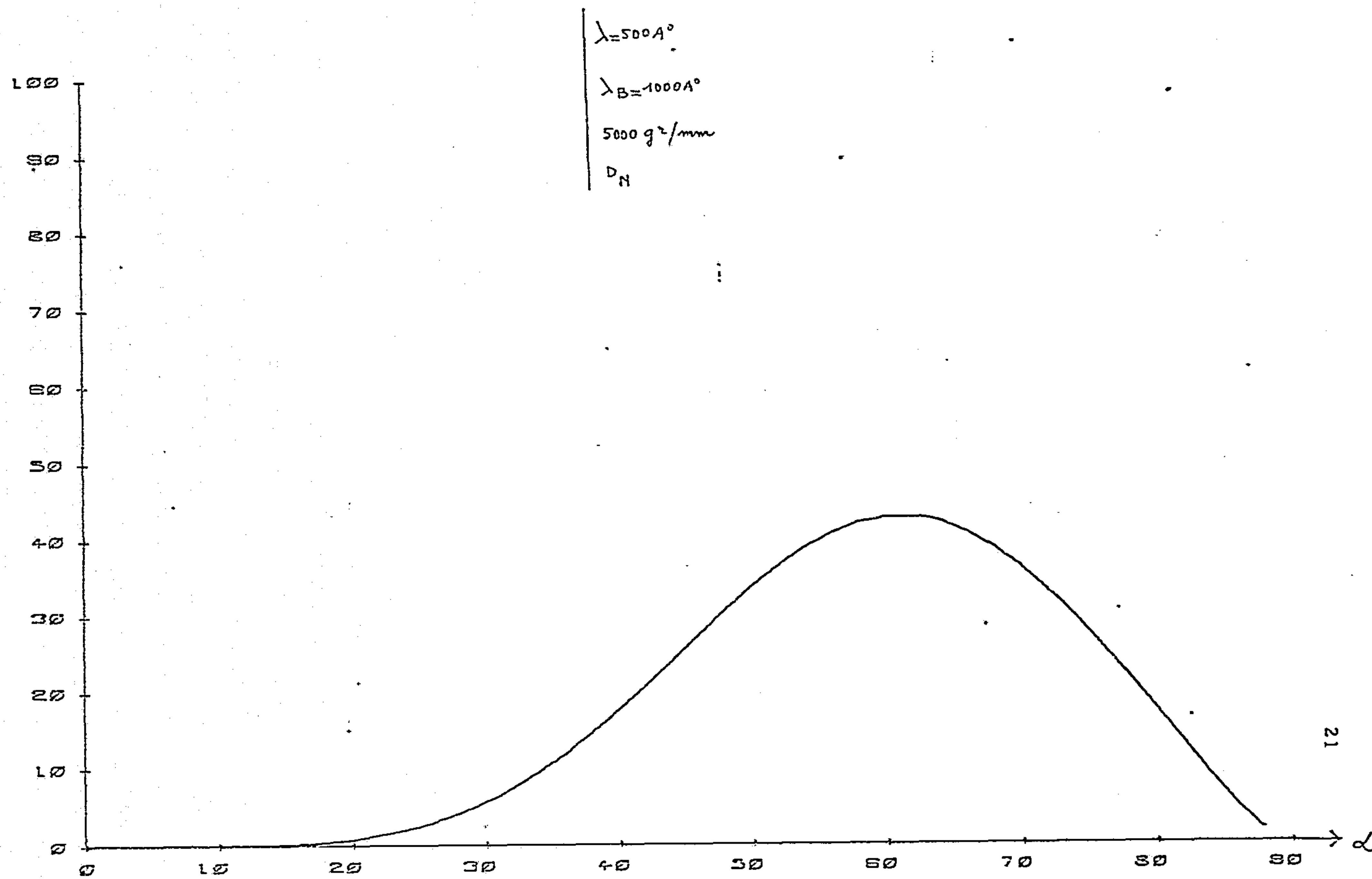
60
70
80
90
α


λ=500A°
λB=1000A°
5000 g²/mm
DN
100
90
80
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10
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0
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20
30
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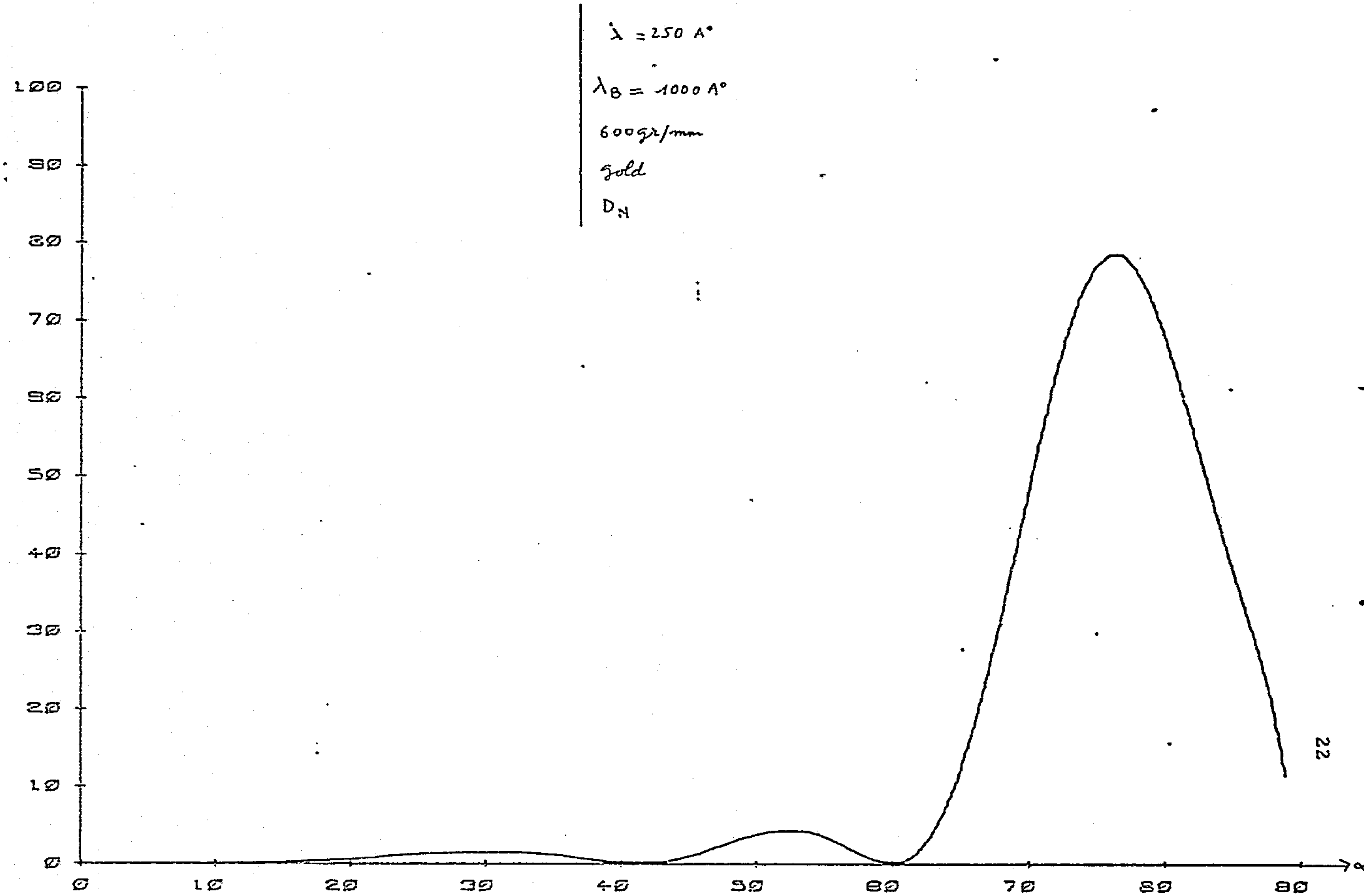
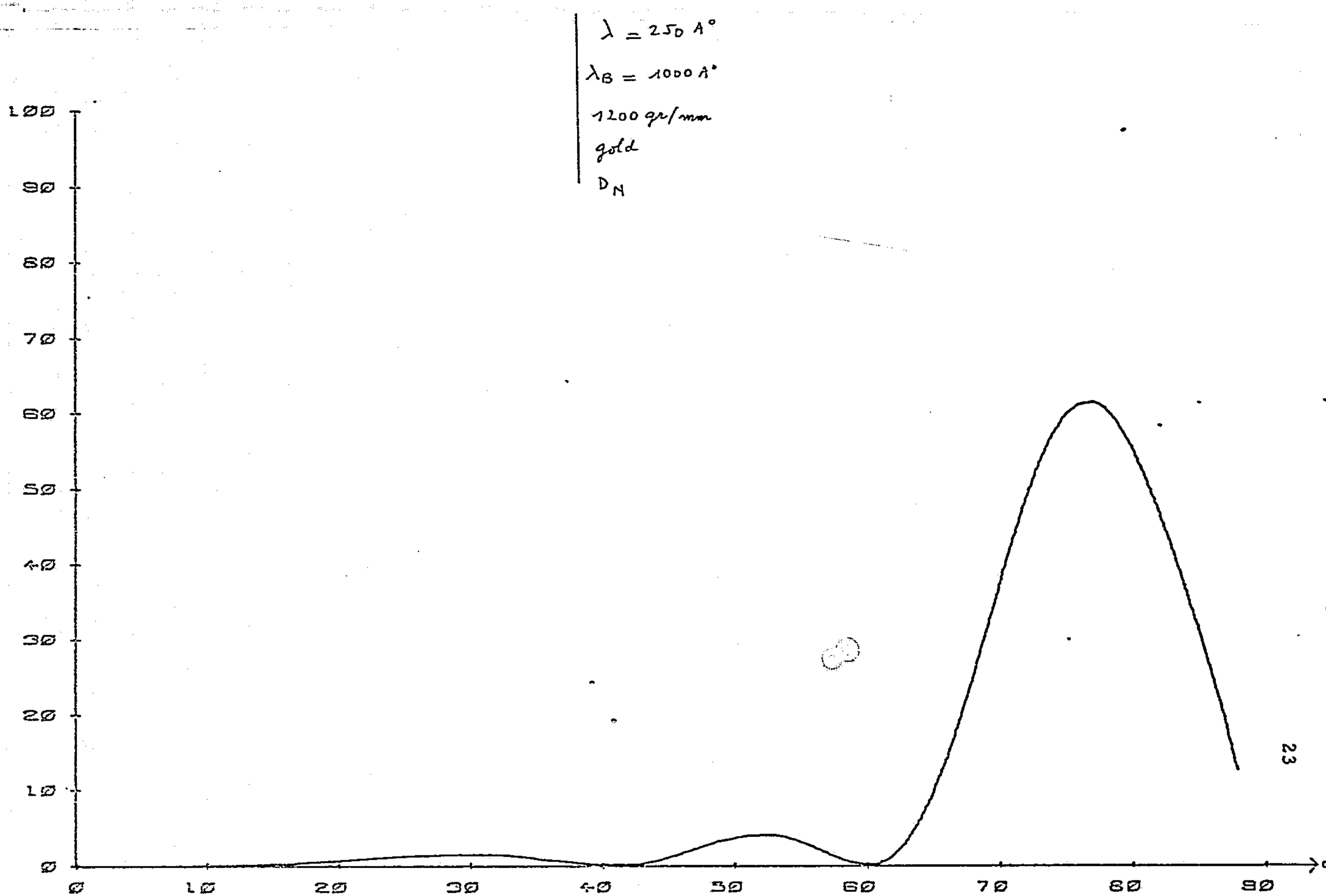
50
60
70
80
90
α


$\lambda = 250$ A°
$\lambda_B = 1000$ A°
600gr/mm
gold
D_N
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α


λ = 250 A°
λB = 1000 A°
1200 gr/mm
gold
DN
100
90
80
70
60
50
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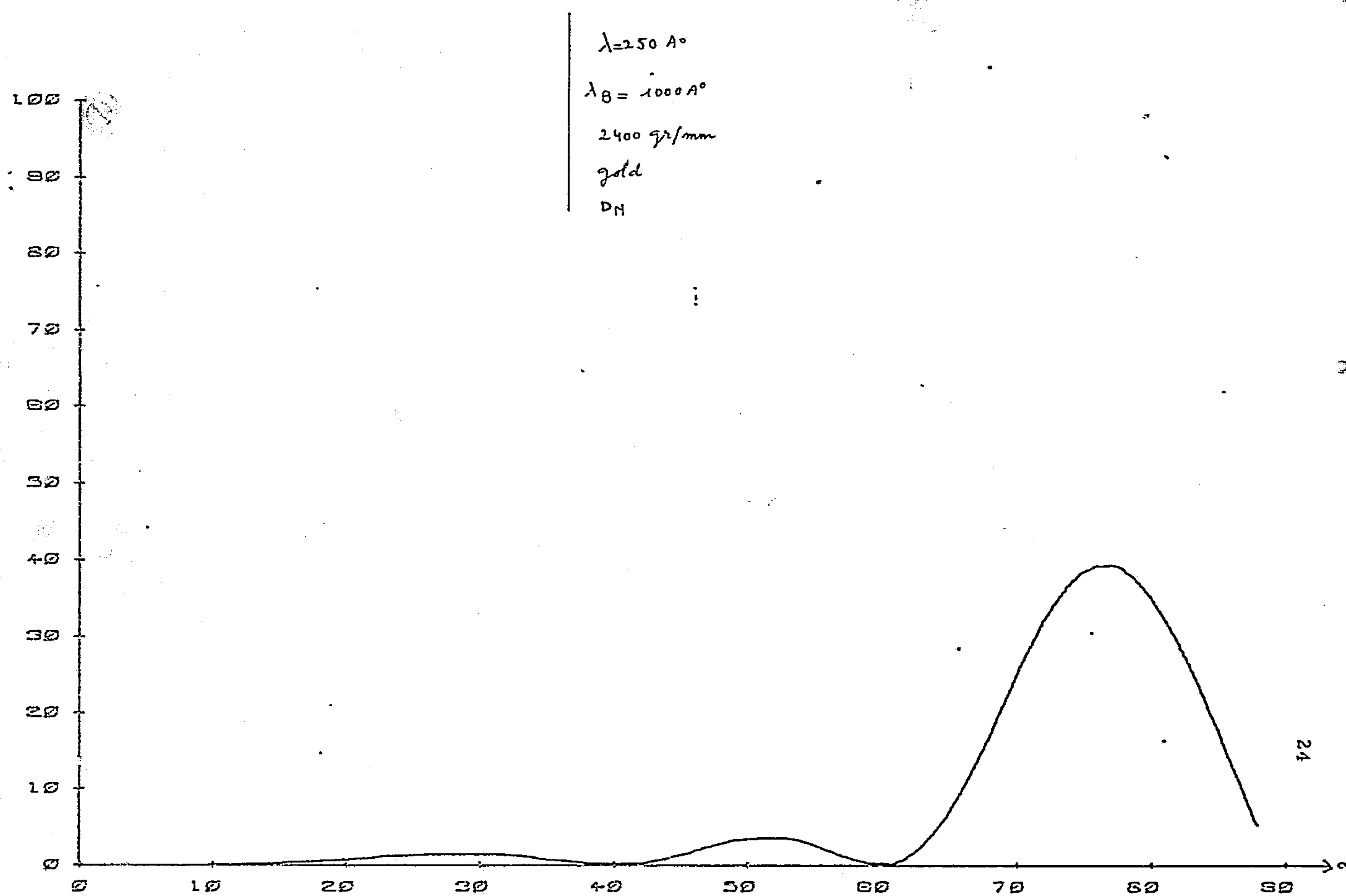
α


λ=250 A°
λB = 1000 A°
2400 gr/mm
gold
DN
100
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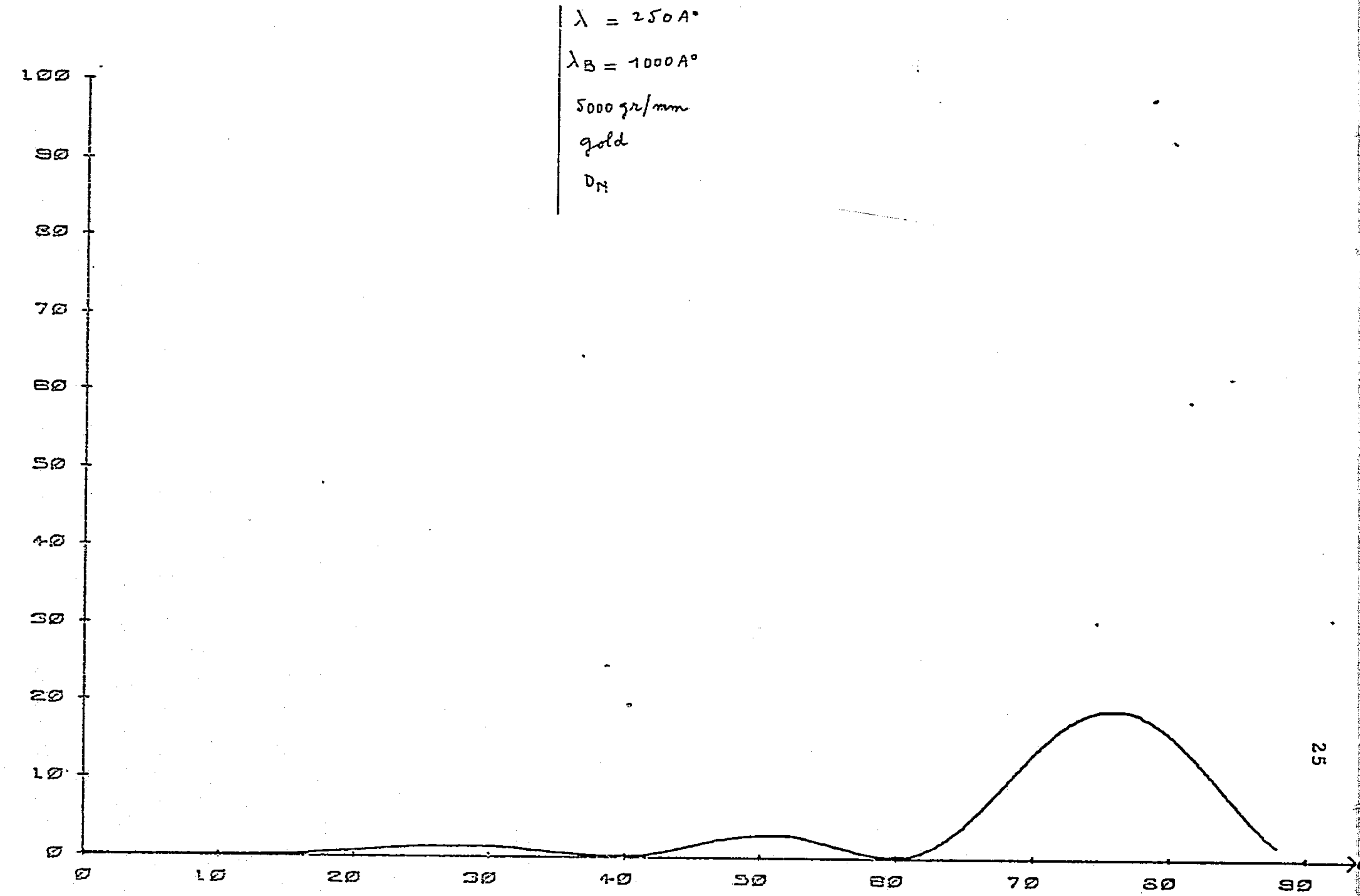
α



λ = 250 A°
λB = 1000 A°
5000 gr/mm
gold
DN
100
90
80
70
60
50
40
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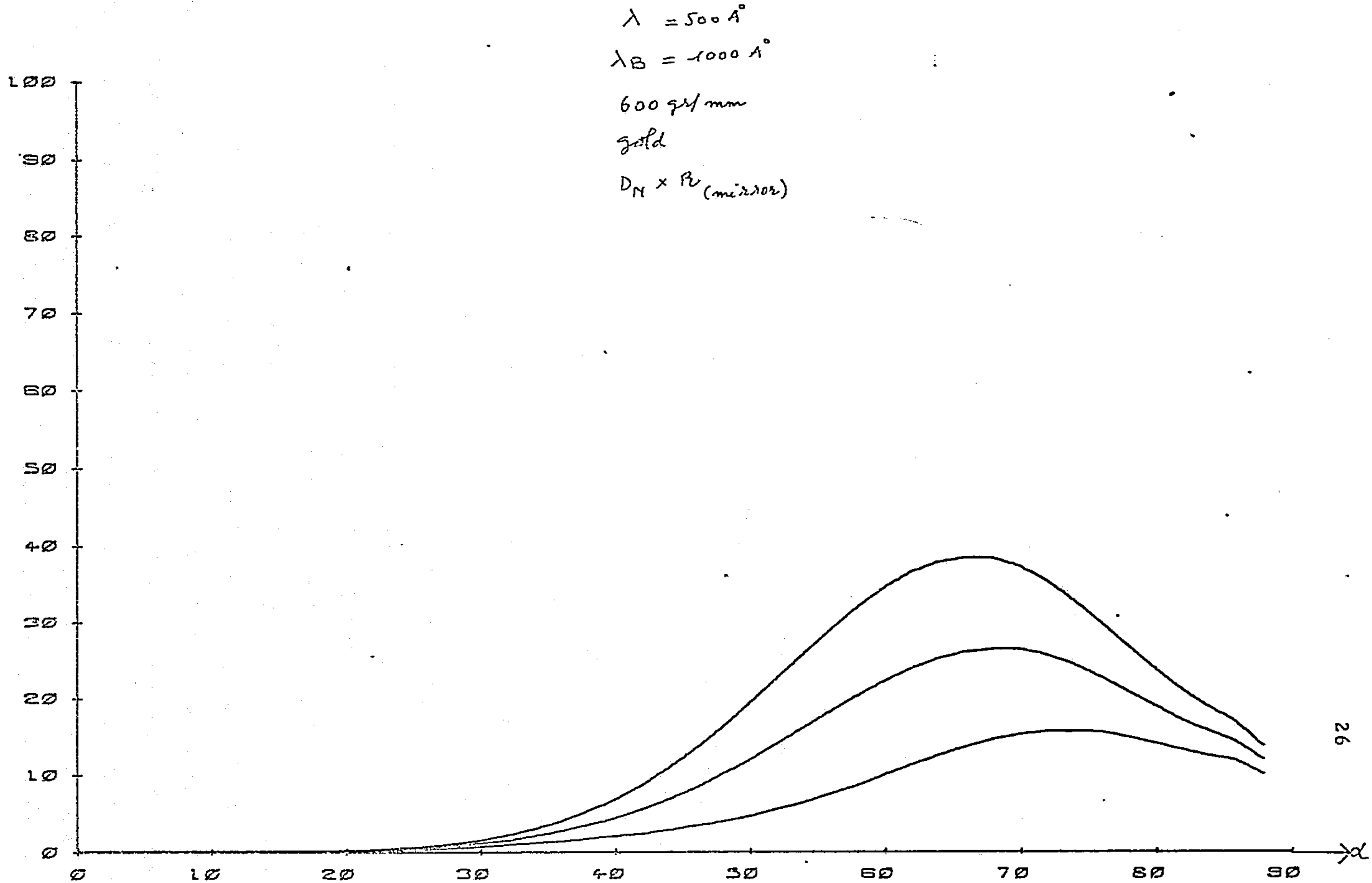
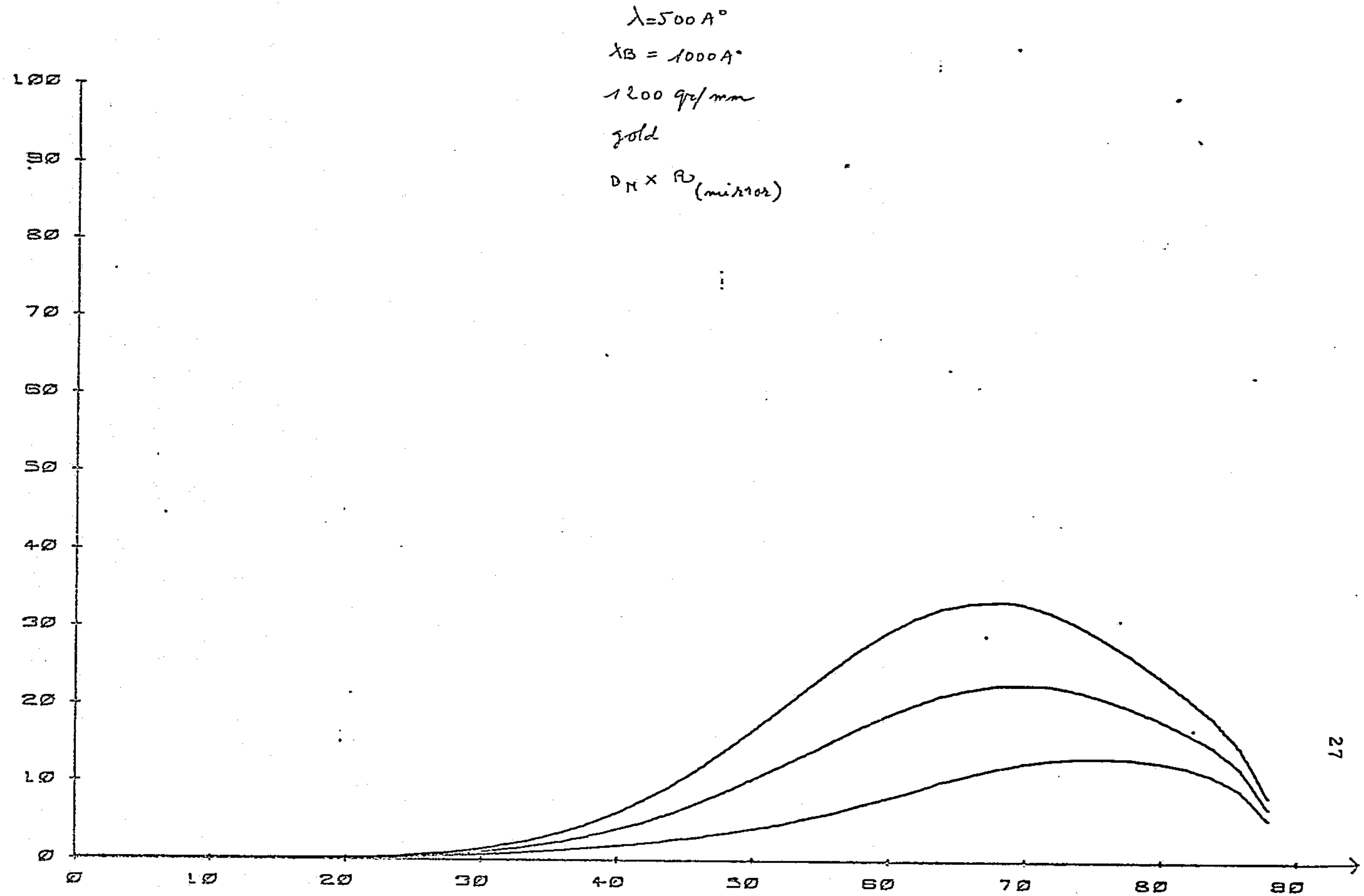
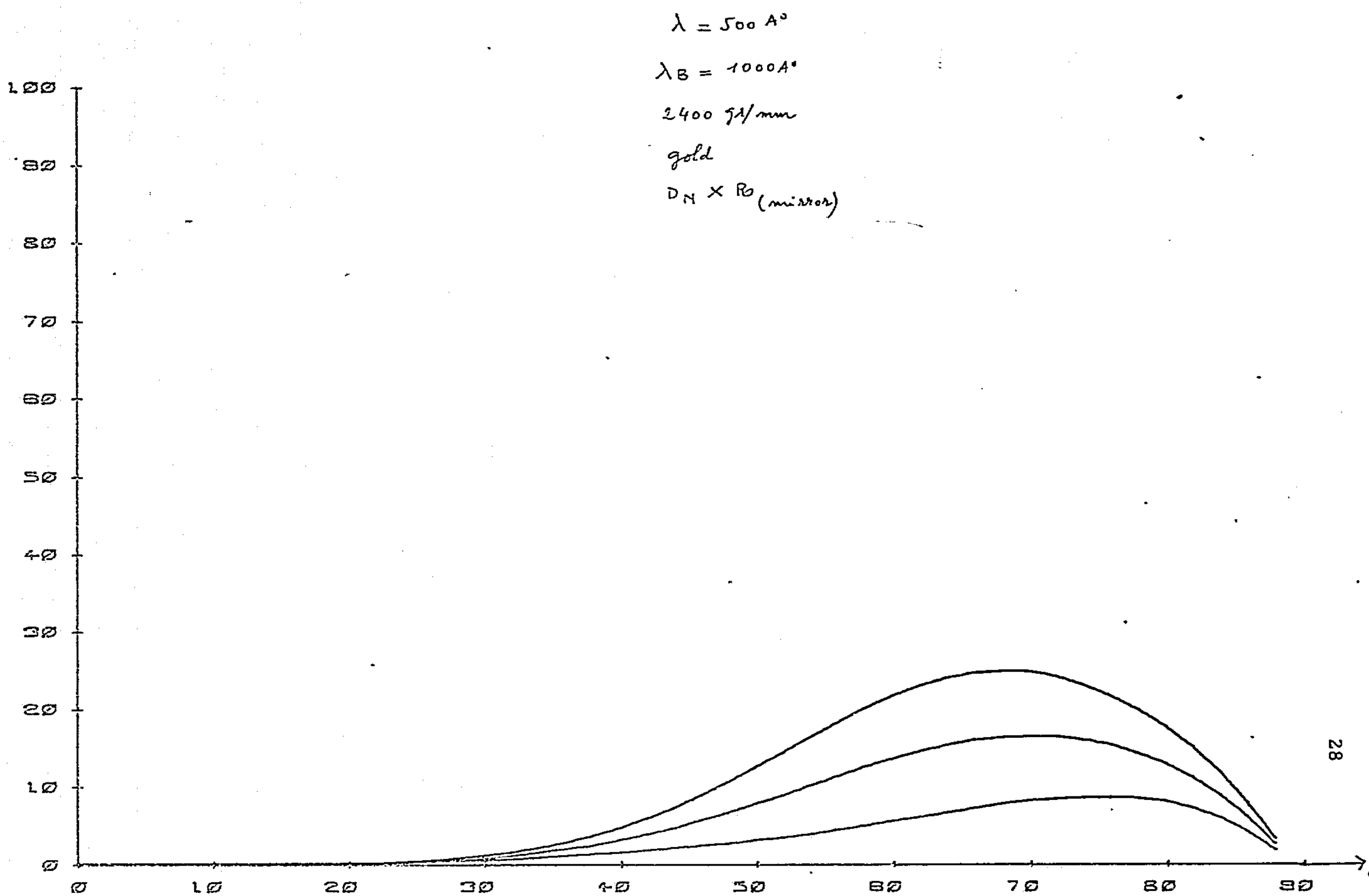
20
10
0
0
10
20
30
40
50
60
70
80
90

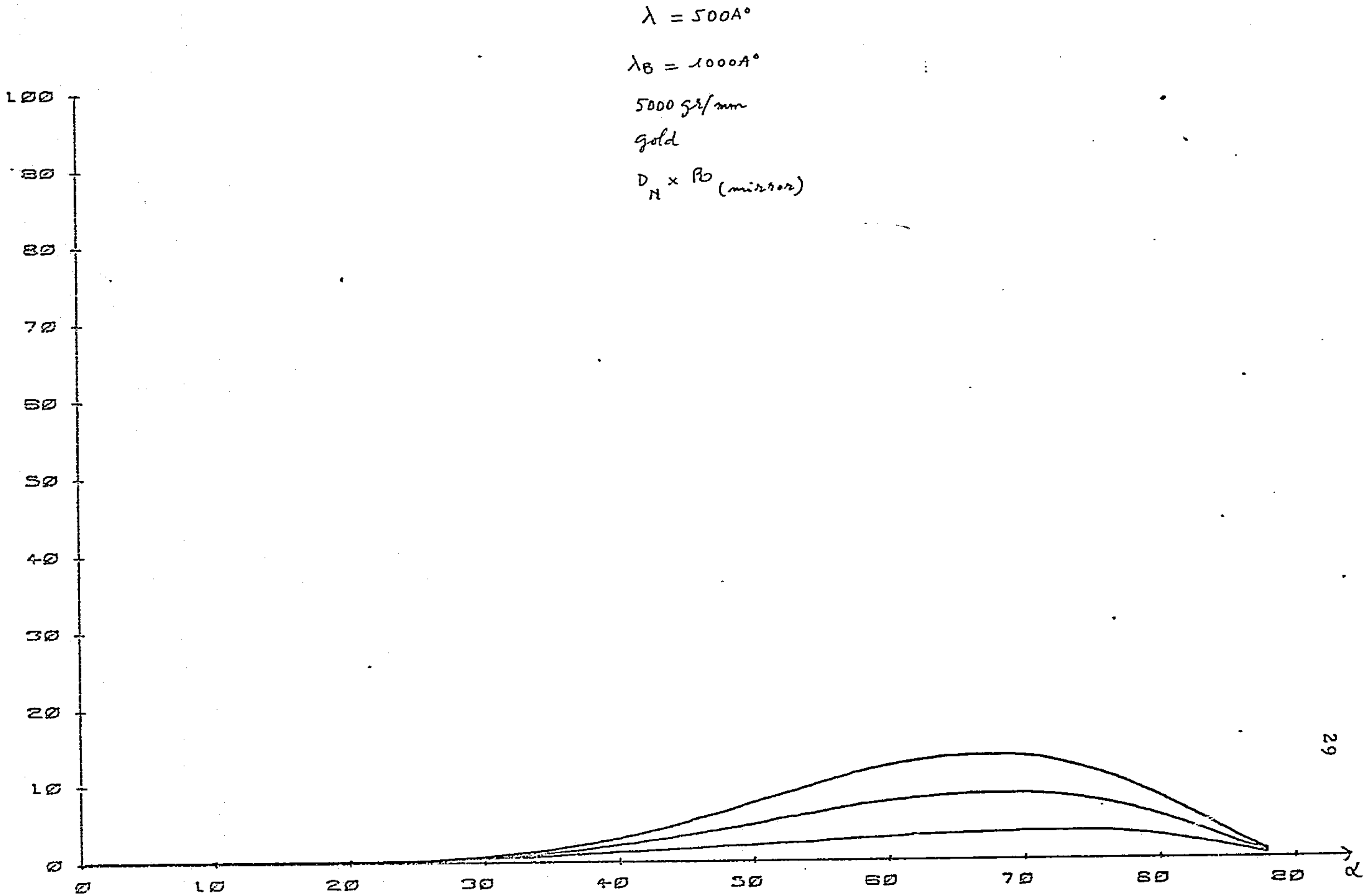

λ = 500 A°
λB = 1000 A°
600 gr/mm
gold
DN × R (mirror)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α

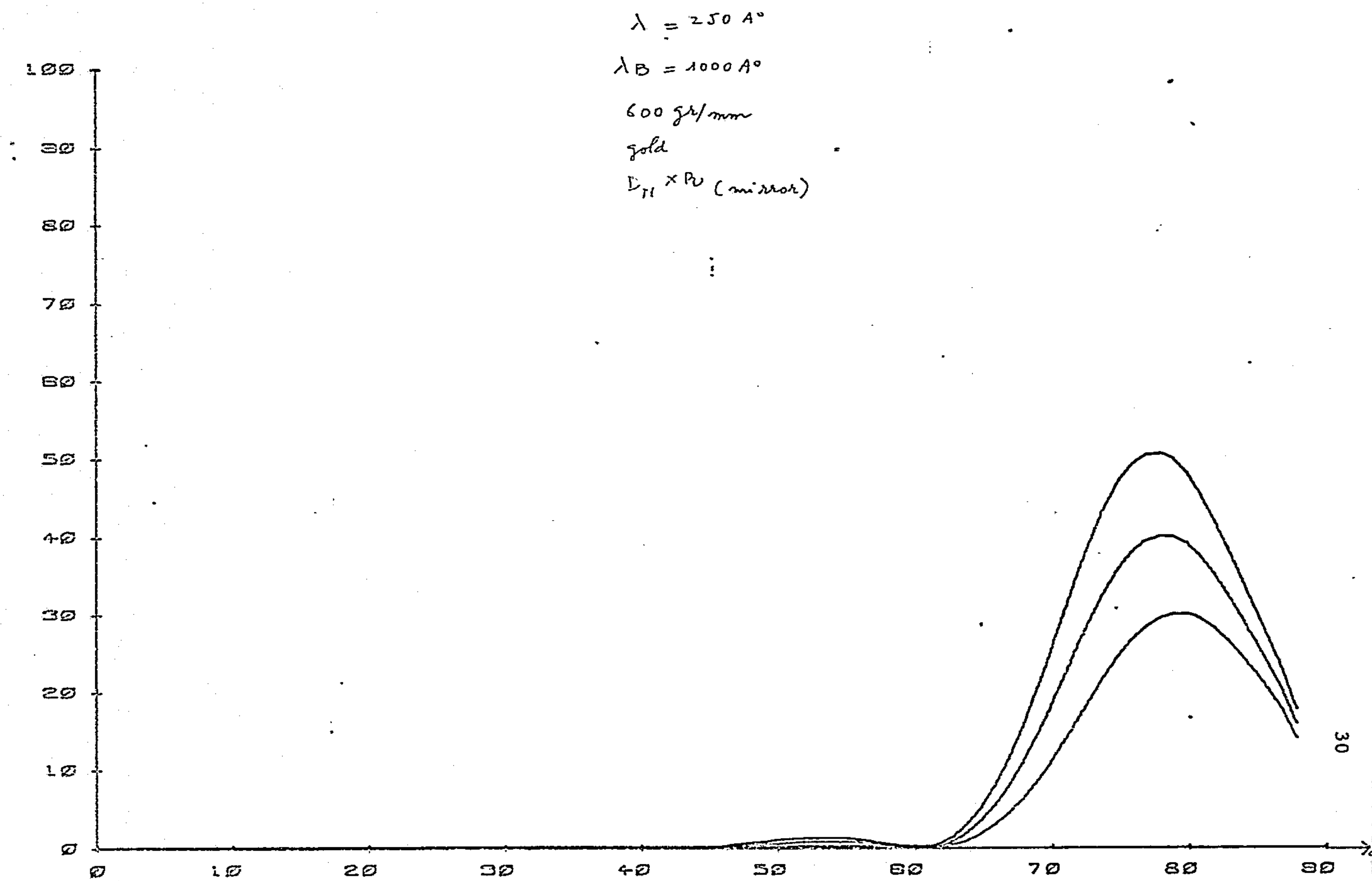

λ=500 A°
λB = 1000 A°
1200 gr/mm
gold
D_H × R_(mirror)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α

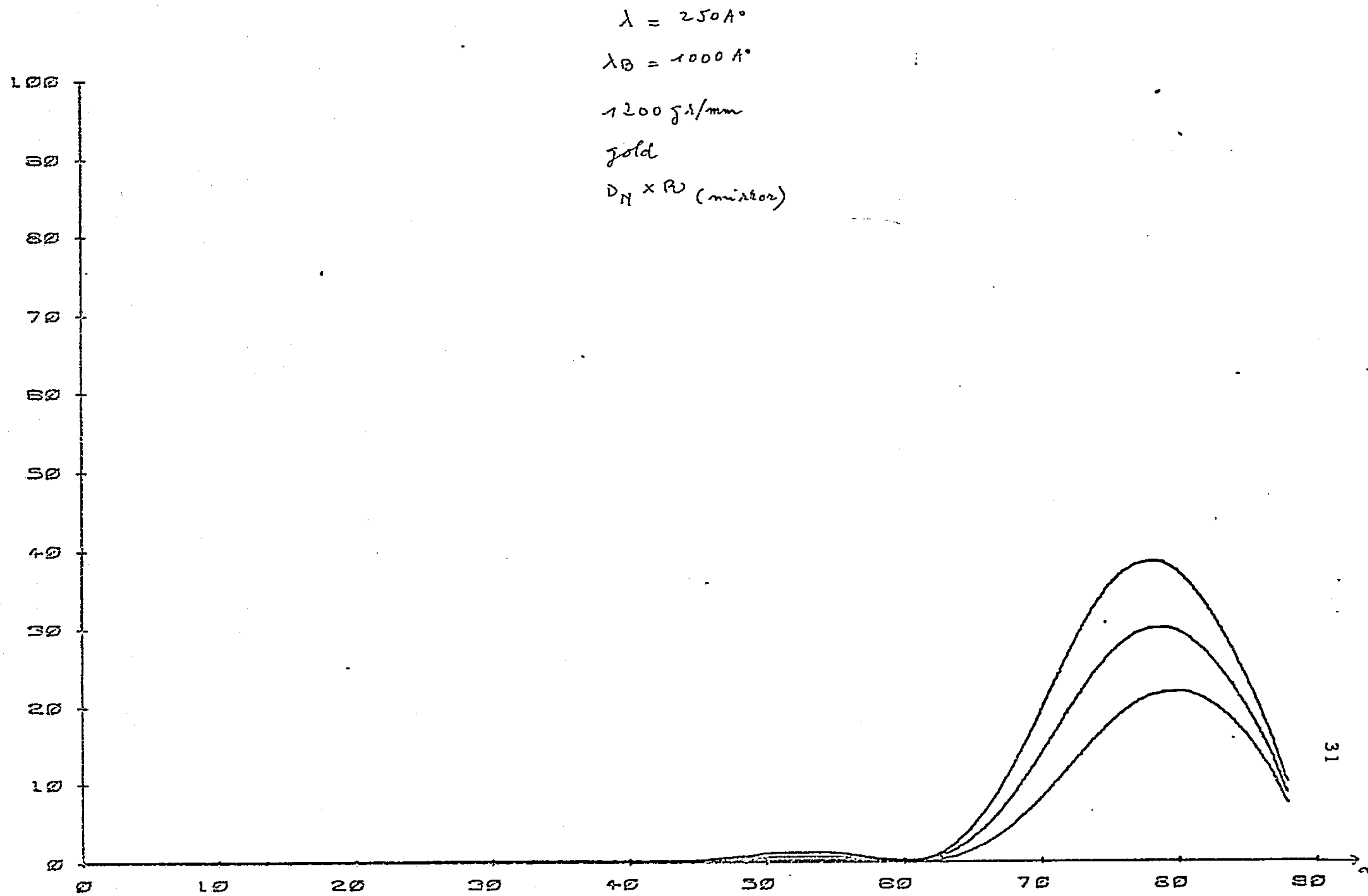


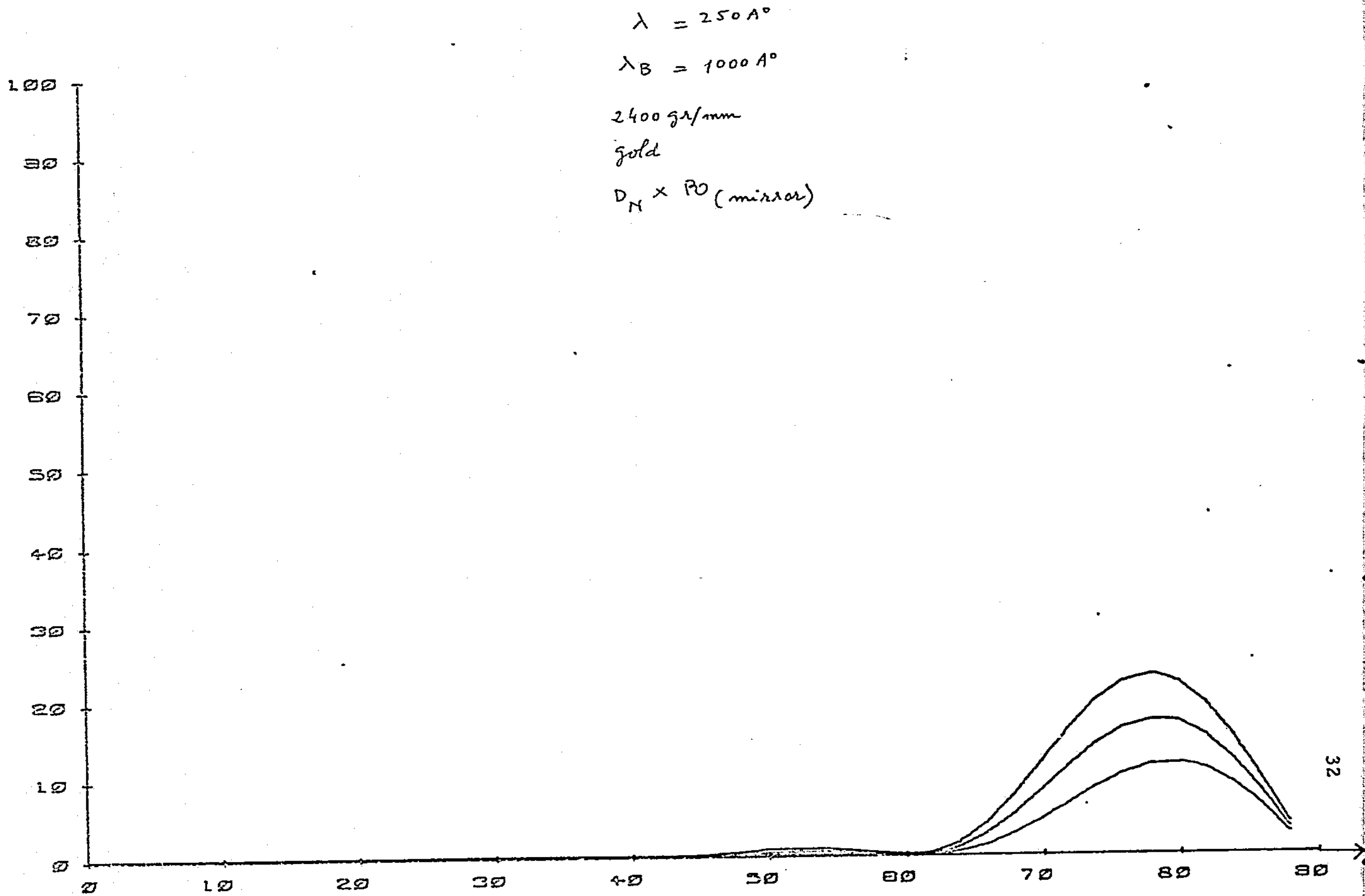
$\lambda = 500$ A°
$\lambda_B = 1000$A°
2400 gl/mm
gold
$D_N \times R_{(mirror)}$
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α

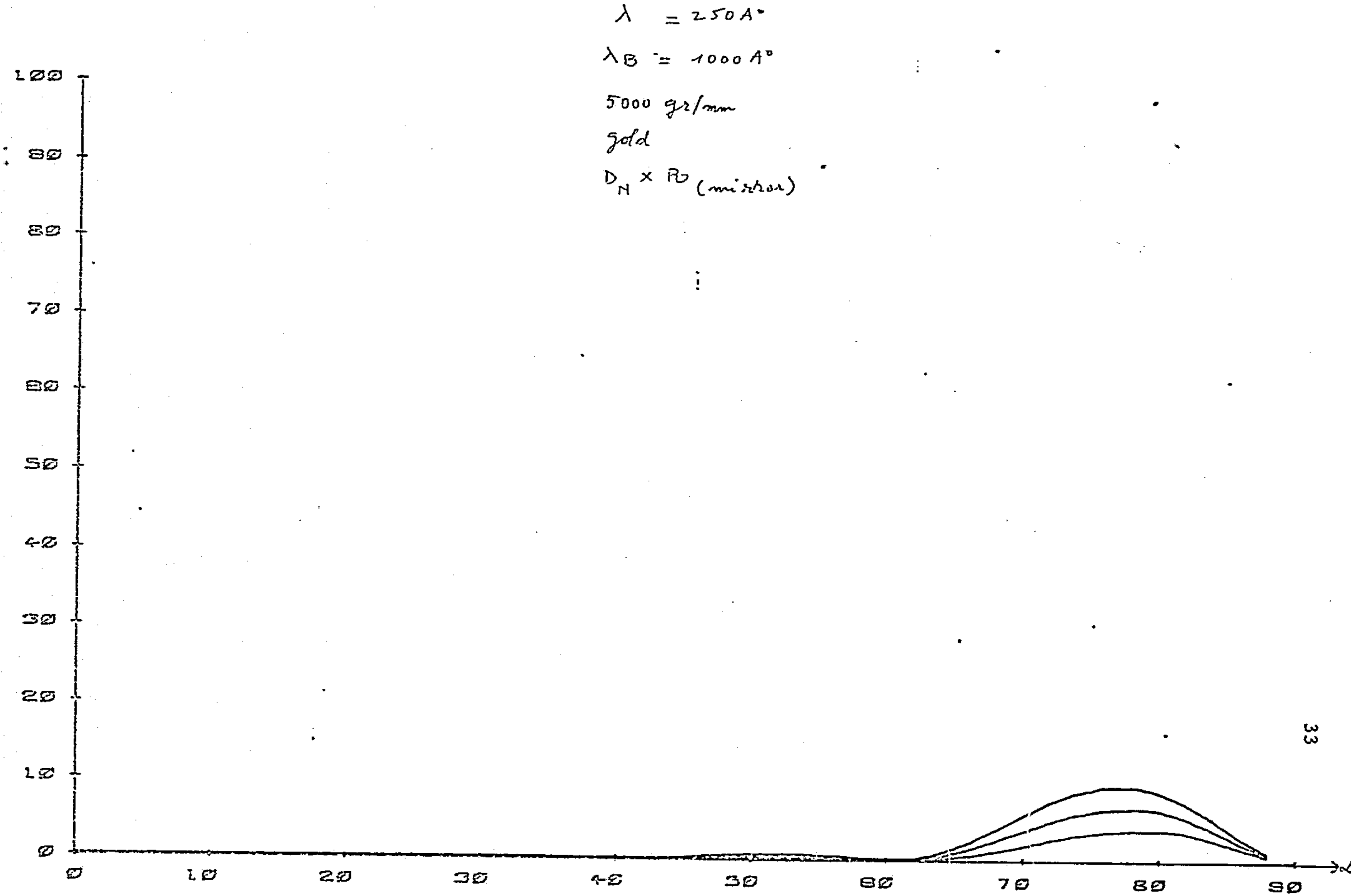
28

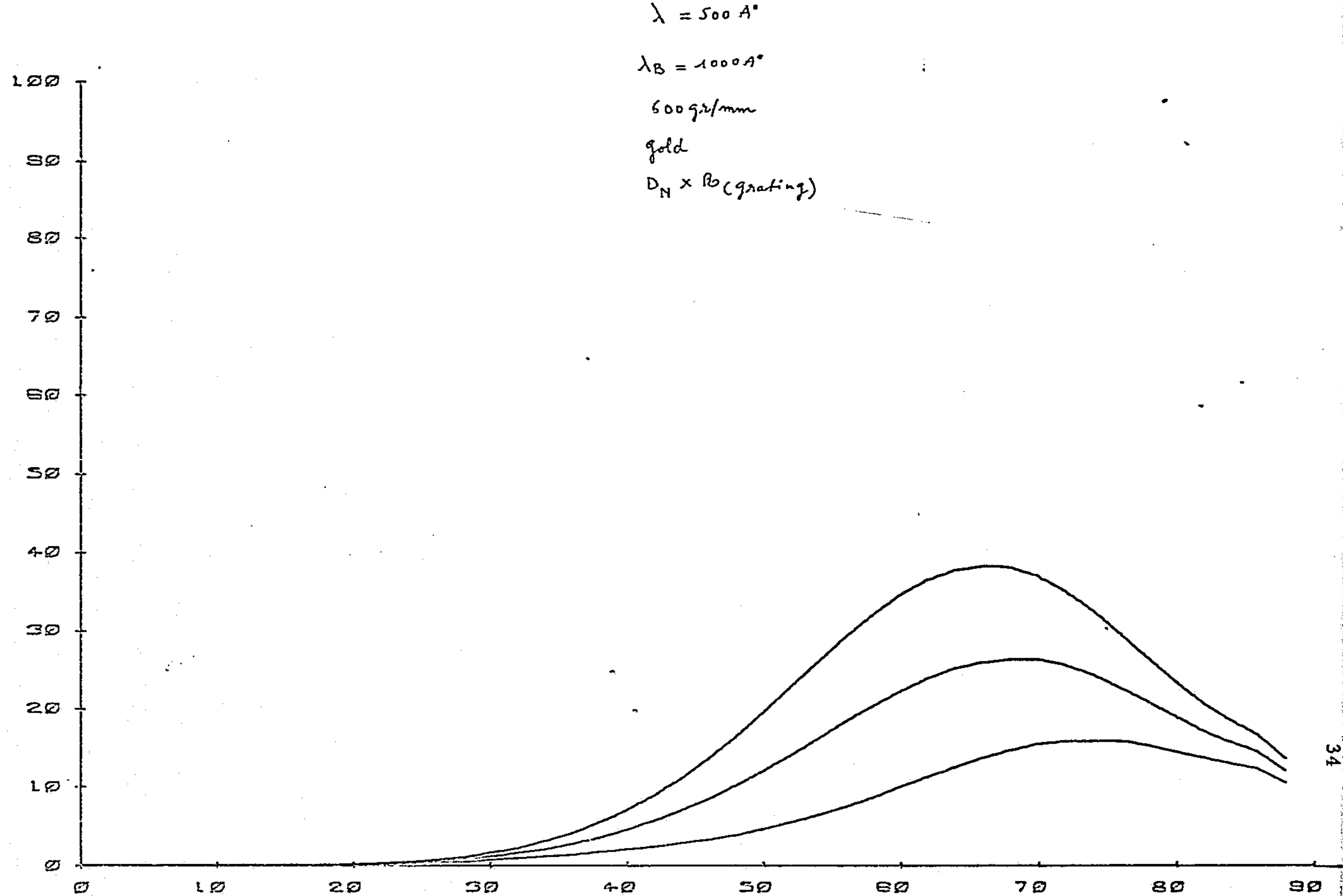

λ = 500A°
λB = 1000A°
5000 gr/mm
gold
D N × R0 (mirror)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α

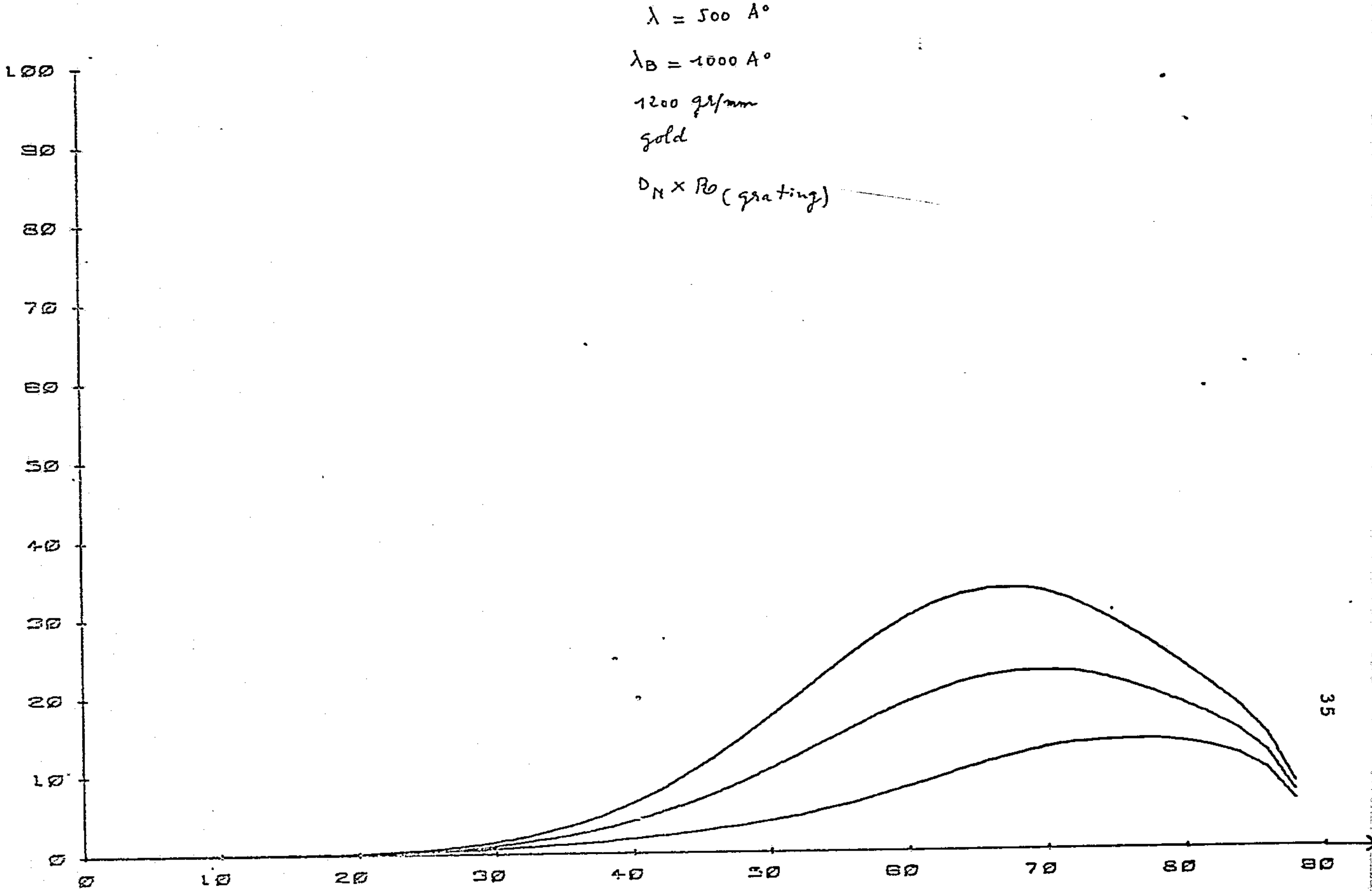

λ = 250 A°
λB = 1000 A°
600 gr/mm
gold
D_II × Ru (mirror)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90

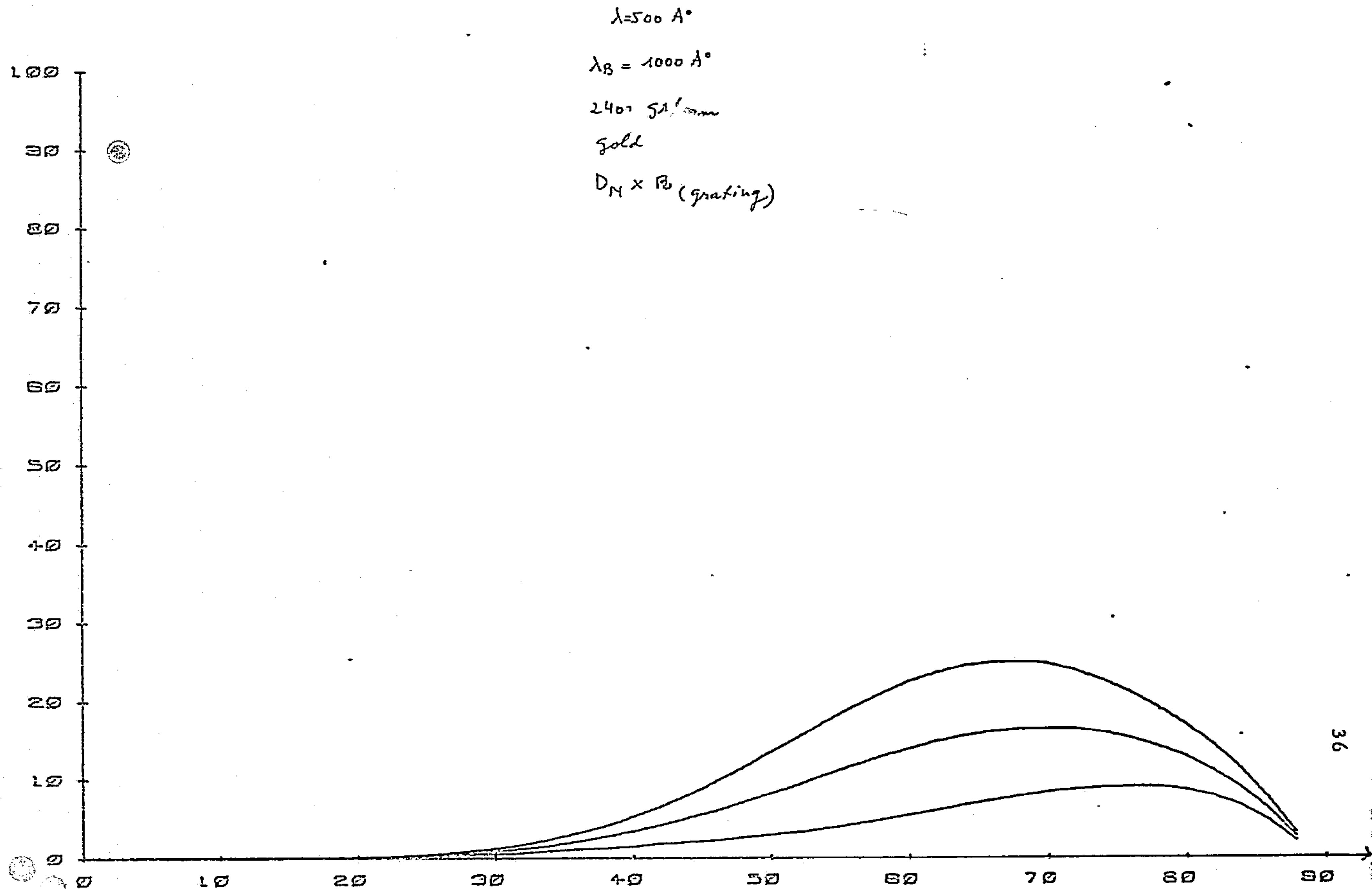

λ = 250 A°
λB = 1000 A°
1200 gr/mm
gold
DN x R (mirror)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α

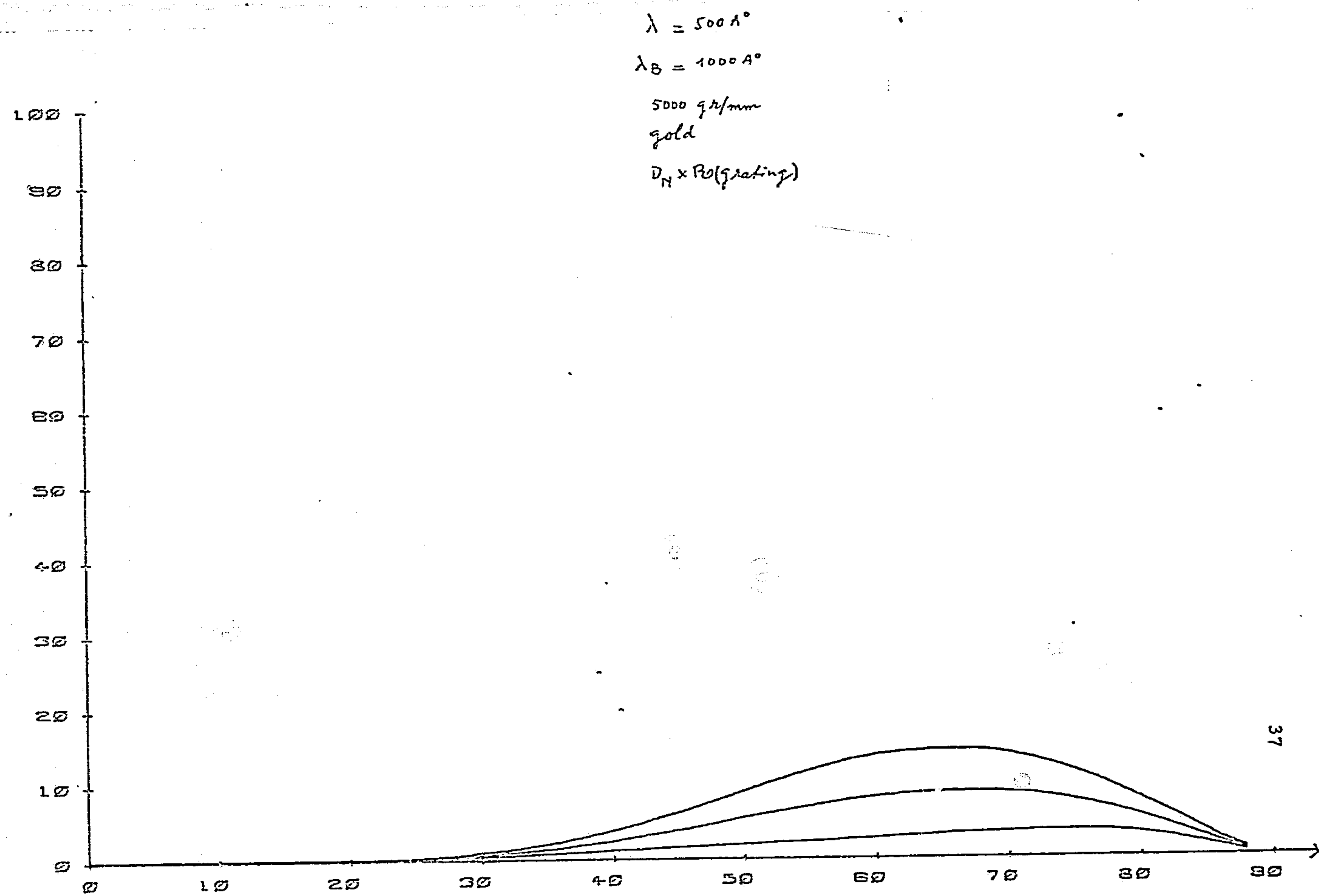

λ = 250 A°
λB = 1000 A°
2400 gr/mm
gold
DN × RO (mirror)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90


λ = 250 A°
λB = 1000 A°
5000 gr/mm
gold
DM × R (mirror)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α

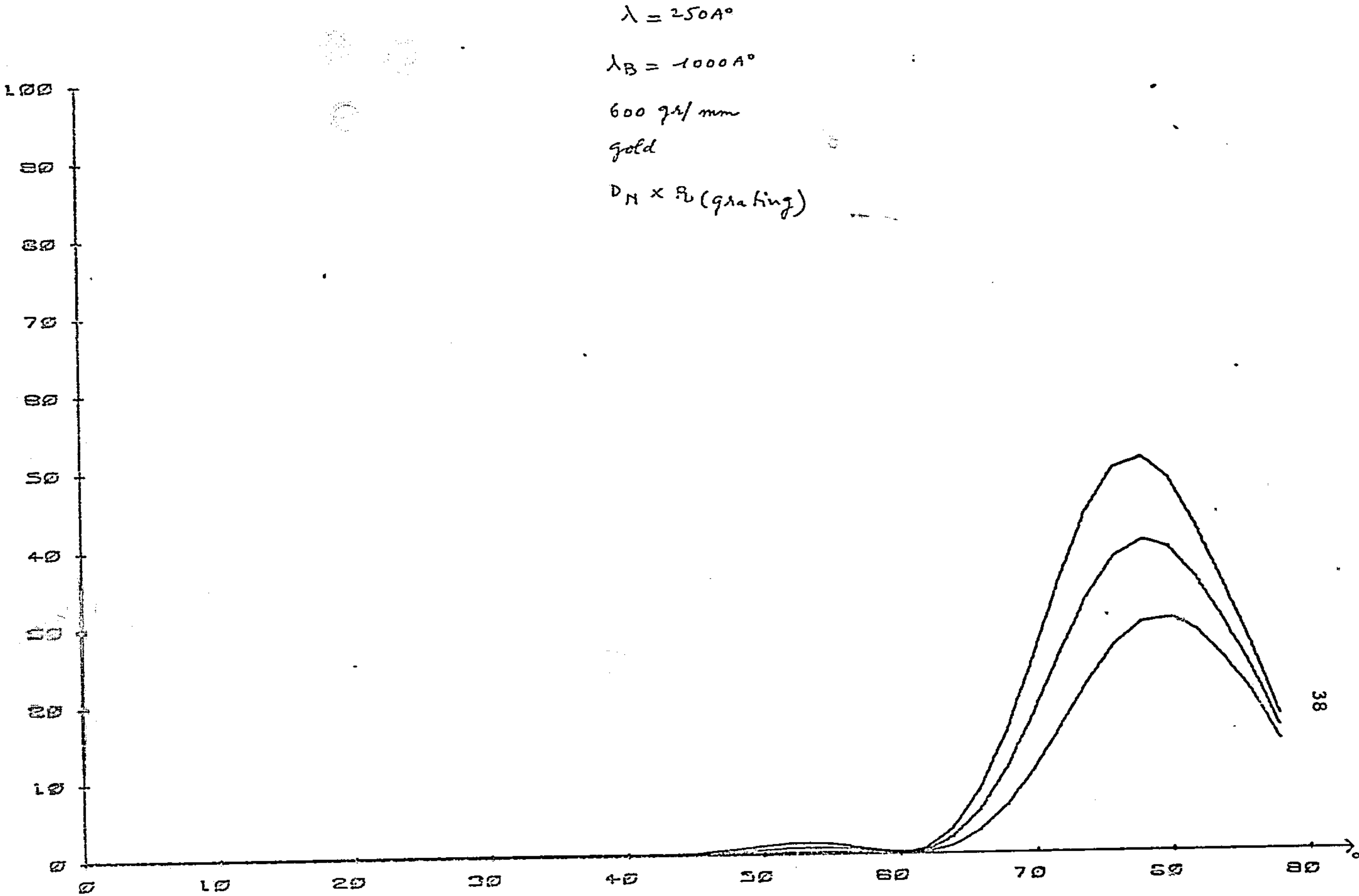

λ = 500 A°
λ_B = 1000 A°
600 gr/mm
gold
D_N × Ro (grating)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90

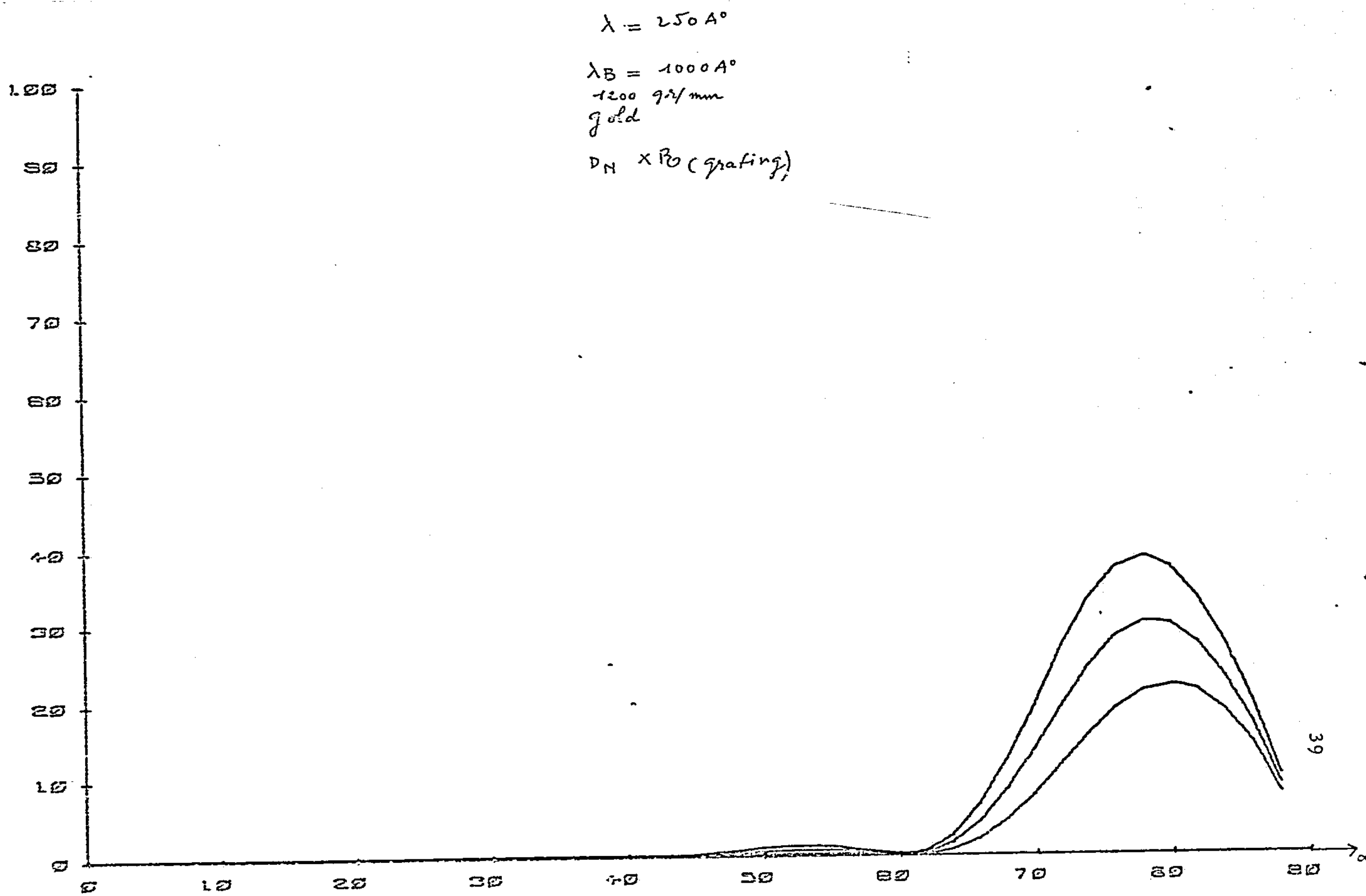

λ = 500 A°
λB = 1000 A°
1200 gr/mm
gold
DN × RG (grating)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90

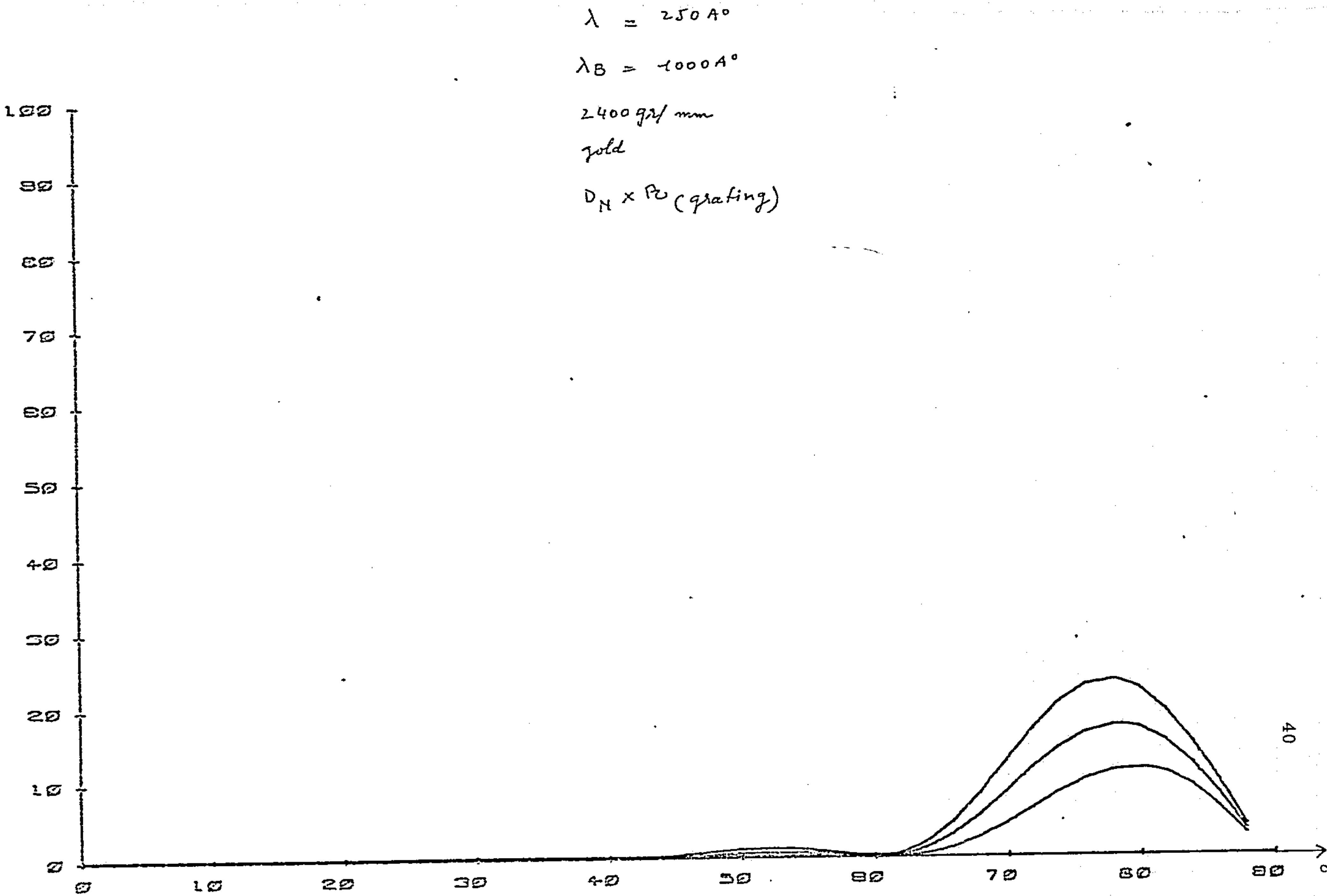

λ=500 A°
λB = 1000 A°
2401 gr/mm
gold
DM × R (grating)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90



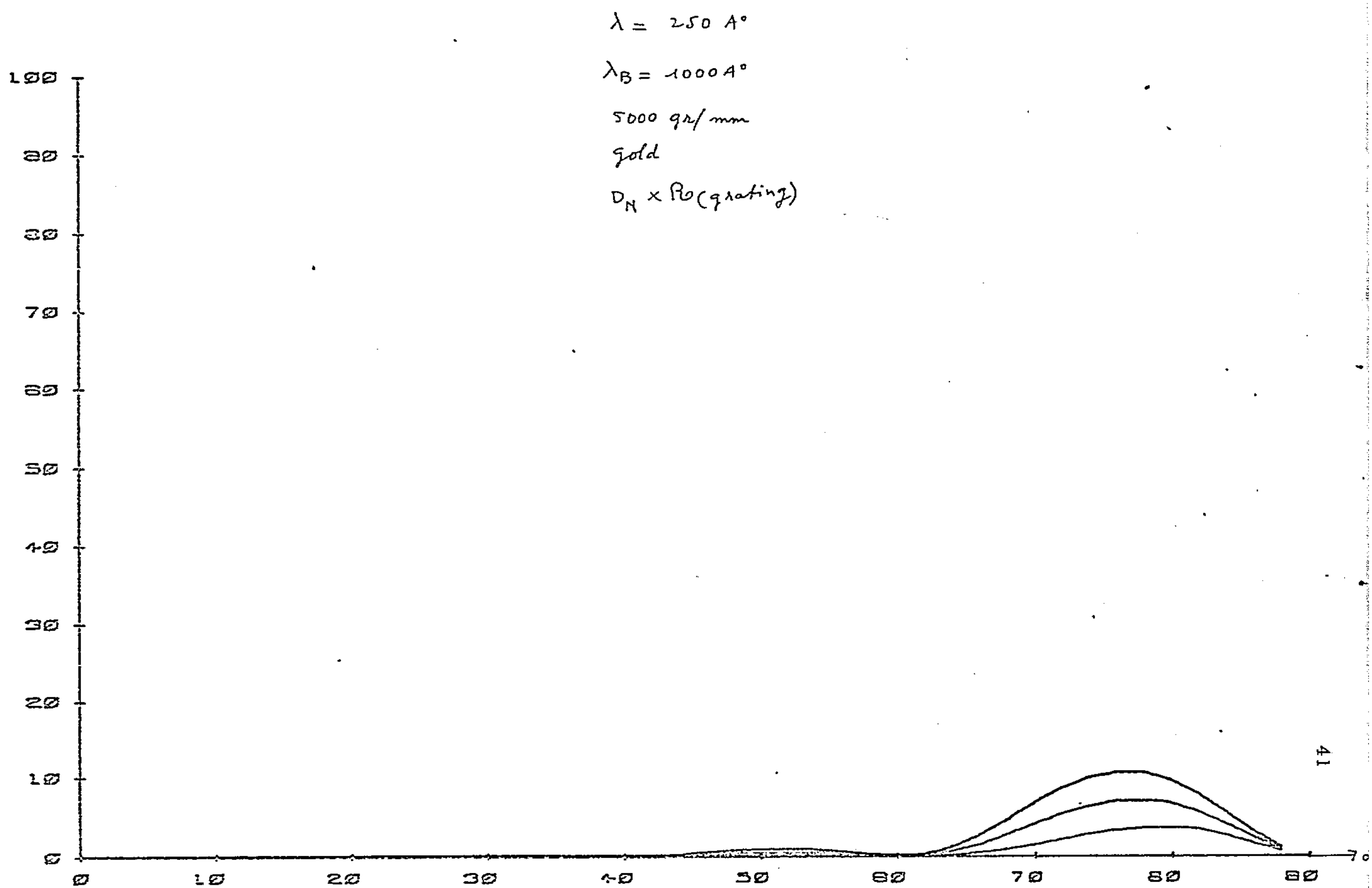
$\lambda = 500$ A°
$\lambda_B = 1000$ A°
5000 gr/mm
gold
$D_N \times$ Ro(grating)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90


λ = 250A°
λB = 1000A°
600 gr/mm
gold
DN × R (grating)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
80
α


λ = 250 A°
λB = 1000 A°
1200 gr/mm
gold
DN × R0 (grating)
1.00
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α



$\lambda = 250 A°$
$\lambda_B = 1000 A°$
2400 gr/mm
gold
$D_N \times R$ (grating)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
α


$\lambda = 250$ A°
$\lambda_B = 1000$ A°
5000 gr/mm
gold
$D_N \times R_0$(grating)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90